

Historical development of concentrating solar power technologies to generate clean electricity efficiently – A review



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ABSTRACT

The conventional ways for generating electricity around the world face two main problems, which are gradual increase in the earth's average surface temperature (global warming) and depleting fossil fuel reserves. So switching to renewable energy technologies is an urgent need. Concentrating solar power (CSP) technologies are one of renewable technologies that are able to solve the present and future electricity problems. In this paper the historical evolution for the cornerstone plants of CSP technologies to generate clean electricity was reviewed and the current projects worldwide of CSP technologies were presented to show that the CSP technologies are technically and commercially proven and have the possibility for hybridization with fossil fuel or integration with storage systems to sustain continuous operation similar to conventional plants. Among all solar thermal technologies parabolic trough is the most technically and commercially proven. It also has the possibility for hybridization since it is proven by operating in several commercial projects for more than 28 years. It has a high maturity level and able to provide the required operating heat energy either as a stand-alone or in hybrid systems at the lowest cost and lower economic risks. For this reason, this technology is dominant in the operational and under-construction projects. However, currently there is a trend toward employing the other CSP technologies in the future projects as a result of the improvement in their performance. The use of PTC technology in the operational CSP projects is 95.7% and has decreased to 73.4% for the under-construction projects. Meanwhile, the uses of Fresnel collector (LFC), Tower power (TSP) and Stirling dish (SDC) technologies in the operational projects are 2.07%, 2.24%, and 0% respectively and have increased to 5.74%, 20.82% and 0.052% respectively for the under-construction projects. For the development projects, the use of TSP technology has reached to 71.43%, compared to 28.57% for PTC.

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1. Introduction

Nowadays, generating electricity by burning fossil fuel faces a lot of problems such as continuous increase of fossil fuel's price and fear of running out [168,170]. Additionally, burning of fossil fuels is the main cause of increasing concentration of carbon dioxide which leads to change in the natural equilibrium of environment by introducing harmful substances or emission of chemical gases into the atmosphere [1]; therefore there is an urgent need to reduce our dependence on fossil fuel for electricity production around the world by using renewable technologies that use natural fuel such as sun energy to generate clean electricity in order to avoid the occurrence of a major global catastrophe and to keep the fossil fuel reserves in the ground.

Concentrating solar power (CSP) technologies are one of the renewable technologies that play a major role in solving the present and future electricity problems [2] because they utilize the sun's heat, which is unrestricted and a daily available energy source. Besides that, it has the ability to store the sun's heat during the day–light to reuse it during day–night, which makes them the most cost-effective technologies among the renewable technologies and competitive with the fossil fuel power plants [8].

Currently, there are four CSP technologies, which are parabolic trough technology where the pioneer system was built and demonstrated in Meadi, Egypt, in 1913 ([5] cited in [14]), linear Fresnel collector where the first prototype was built and demonstrated in Genoa, Italy, in 1964 [12], the Stirling/dish system where the first prototype was built and demonstrated in Southern California during 1982–1985 [206,207], and the earliest solar tower power that was demonstrated by constructing a plant named EURELIOS to generate 1 MWe in Adrano, Sicily, Italy, in 1965 [6]. The ability of the solar tower technology to generate large scale electricity (10 MWe) was demonstrated by Solar One plant that was built in California, U.S., in 1982 [7]. The first commercial CSP plant worldwide named SEGS I was built in California in 1984 by using parabolic trough collector technology to generate 14 MWe; then the capacity of the SEGS plants was increased to 354 MWe by 1990 [2].

Between the year 1991 and 2005 no solar thermal power plants were built anywhere in the world; but since 2006, there is a continuous growth in the construction of the CSP plants because of increasing thermal efficiency and the capacity factor of these technologies [4], and their ability to limit the GHG emissions and other environmental impacts of energy generation higher than other renewable technologies; they reduce approximately 1 kg of average GHG emissions for each kW generated by them [9]. In addition to what is mentioned above, CSP technologies generate electricity from free and undiminished source, which leads to contribution in raising the economy of countries having high direct normal irradiation (DNI) and cheap land [4]. Nowadays, Spain is considered the largest producer of electricity using the CSP technologies. Meanwhile, there are several very large solar

thermal plants planned or under construction in the United States and other countries [225–239].

This paper provides a comprehensive review on the historical development and current projects of four CSP technologies in the world. It covers the success stories of the initial projects that were used to demonstrate the ability of these technologies to utilize the sun's heat to produce dry/superheated steam used for driving the conventional generators. Also it covers the current projects worldwide to show the current situation and the future prospects for the CSP technologies in the world and to show that most of the CSP technologies are commercially available and they have the possibility to hybrid with fossil fuel plants or integrate with storage systems in order to make the CSP plants utilize its power block for 24 h similar to conventional power plant. The paper presents general descriptions, historical development, current projects and summary of the CSP technologies. This paper is considered the first academic work that provides the comprehensive review on the historical development of the four CSP technologies and its current situation.

2. Concentrating solar power plant (CSPP)

CSPP consists of two fields that are solar field and power block. The solar field comprises of many arrays that are arranged in a certain manner and each array consists of modules (concentrators). These modules are mirrors that concentrate the sun's heat by reflecting it to a point or line receiver to produce heat at medium (about 400–550 °C) or high (about 600–1000 °C) temperatures. Then, this concentrated heat transfers to the fluid (thermal oil, molten salt, water, air, hydrogen or helium) running through the receiver's tubes to produce electricity by driving the conventional generators in the power block [2,16]. Fig.1 shows the principle of operation of CSP plants. Some of the CSPP plants according to the type of the technology used can be integrated with the storage system to store a part of the concentrated heat during the sunrise to generate electricity in the cloudy days or when the sun sets or/and can be hybridized with the fossil fuel to make the plant produce electricity for 24 h in order to improve its thermal efficiency and capacity factor and hence reduce the cost of the technology.

Currently, there are four CSP technologies that have been used worldwide, namely parabolic trough collector, solar tower power, Stirling/dish and linear Fresnel collector. The parabolic trough collector and the linear Fresnel collector technologies are known as line focus technologies because they concentrate the sun's heat along the focal length of the collector, while the Stirling/dish and the solar tower power technologies are known as point focus technologies because they concentrate the sun's heat on point at the tower or at the center of parabolic dish [3].

The line focus technologies focus the sun's radiation about 100 times [17] onto trough located along the parabolic collector or

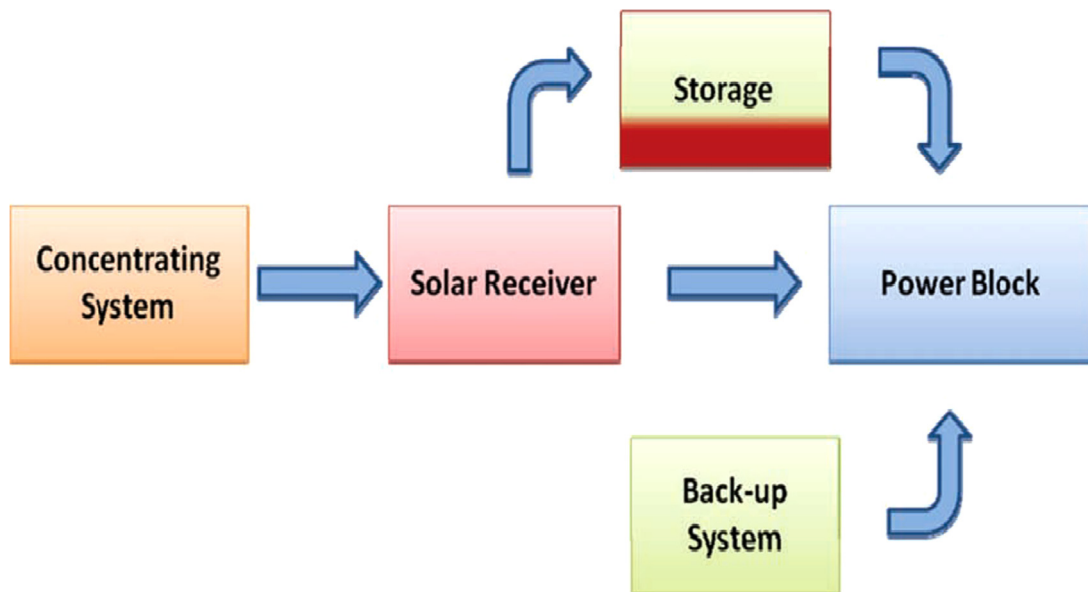


Fig. 1. Principle of operation of CSP plants [19].

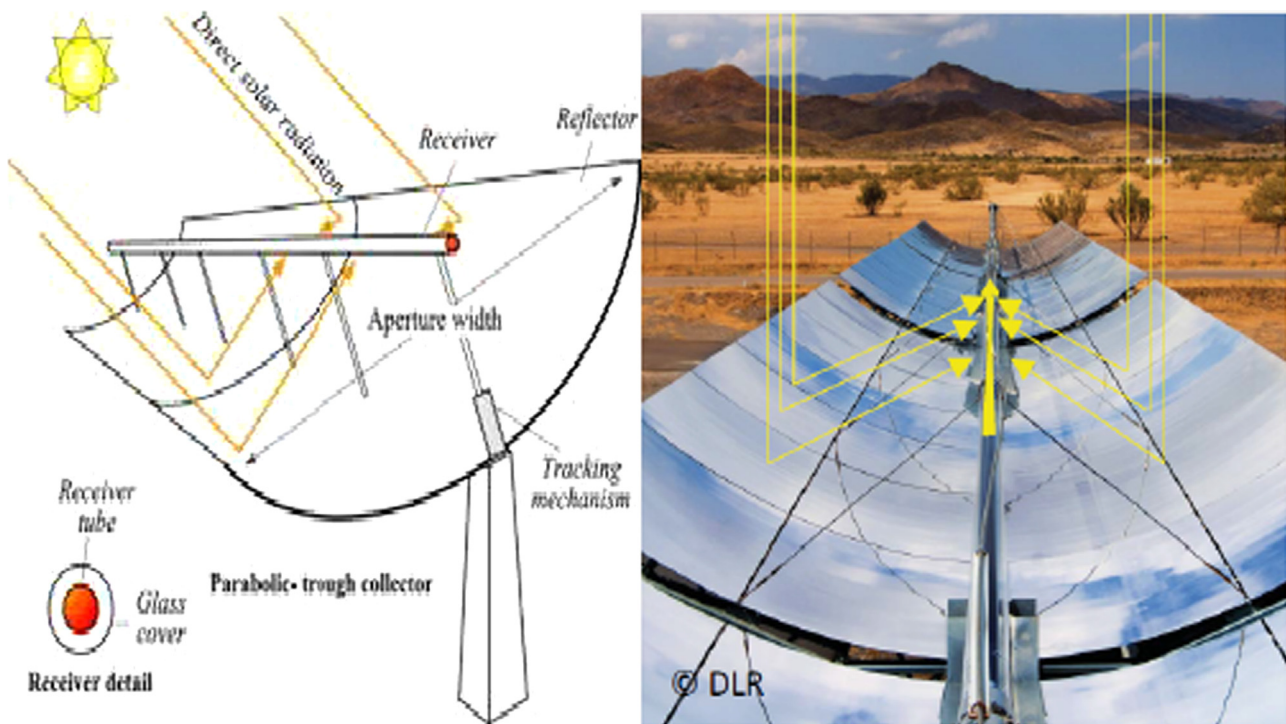


Fig. 2. Parabolic trough collector [19,59].

elevated inverted linear receiver located along the Fresnel collector to produce heat at about 400–550 °C [3,17]. This heat interval has the ability to produce steam at moderate quality, while point focus technologies concentrate the sun's radiation about 1000 times onto receiver located at the top of the tower or at the focus point of the dish to produce heat at about 600–1000 °C, which is double the reached temperature at point in the line focus technique [17]. The difference in reached temperature makes point focus technique more efficient than the line focus technique because it reduces both the land usage, and the effective cost per kWh of the plant [3,18], but the line focus techniques are less expensive and technically less difficult than point focus techniques [3].

3. Parabolic trough collector technology (PTC)

PTC is one axis tracking technology, and it comprises of a million of parabolic-shaped mirrors with a focusing system running along the focal line of it [17]. The mobile collector, which is approximately 12 m long is supported by either aluminum or steel supporting structure and aligned on either a north–south axis or east–west axis. The north–south axis direction provides more energy in summer, while the east–west axis direction provides more energy in winter [25]. The tracking system rotates the collector on its single axis throughout the day to track the DNI of sun's energy, which reflects onto the receiver tube that contains either the synthetic thermal oil, molten salt or pressurized water [17].

The temperature of concentrated heat reaches to 400 °C in case of synthetic thermal oil, 550 °C in case of molten salt or 500 °C in case of pressurized water [2,16]. This heat temperature either transports by the synthetic thermal oil or molten salt working fluid to train intermediate heat exchangers for exchanging it with the working fluid of conventional Rankine cycle or uses it directly to generate moderate steam in the troughs in case pressurized water is the working fluid. Fig. 2 shows the parabolic trough collector.

3.1. Historical development

Captain John Ericsson in 1864 invented a solar-powered hot air engine using a parabolic concentrator to generate steam that was used to drive his Stirling engine [52]. He is considered the first person to use the solar energy to generate steam that was used for pumping water, but Ericsson's reflector was not advanced beyond the prototype stage until 1913 [54]. In 1913, the first parabolic trough system in the world was built in Maadi, Egypt [60] for generating steam that was used for a 73 kW pump which delivered 2000 m³/h of water for irrigation purposes as stated in [5] (cited in [14]) and in [54]. According to [53] the system consisted of five collectors with the north–south axis tracking system and the length and width of collector were 64 m and 4 m respectively and the spacing between them was 7.6 m. This system succeeded in producing 50–60 Hp continuously for approximately 5 h as [54] reported. Fig. 3 shows the first parabolic trough system in Maadi, Egypt.

Sandia National Laboratories in Albuquerque, New Mexico after 1913 as per [55] conducted or sponsored the development of the parabolic trough system. In the U.S. the development of large-scale parabolic trough system that was able to generate temperatures greater than 500 °C for its use in industrial process heat (IPH) applications had begun in mid-1970s by the Energy Research and Development Administration (ERDA) and continued with the establishment of the U.S. Department of Energy (DOE) in 1978. During that time according to [55], the key manufactures for the parabolic system used for processing heat applications in the U.S. were Acurex, SunTec, and Solar Kinetics, who provided service in several parabolic systems with area ranging from a few hundred to about 5000 m². While in Europe as per [55], the development of the parabolic trough system was taking place in 1980s when International Energy Agency (IEA) constructed a Small Solar Power Systems Project/Distributed Collector System (SSPS/DCS) in Tabernas, Spain in 1981. The project included two solar fields with a total mirror aperture area of 7602 m². Two types of parabolic trough collectors were used in the fields, which are single axis tracking Acurex collectors and the double-axis tracking parabolic trough collectors developed by M.A.N. of Munich, Germany. As per [55,57,58], Luz International Limited (Luz) in 1982, based on the experience that they had gained by DOE/Sandia and the SSPS

projects developed a parabolic trough module for industrial process heat applications.

Acurex Corporation in 1983 signed an agreement with Southern California Edison (SCE) to sell electrical power from parabolic plant that was to be built by corporation; but because the required finance to execute the project was big, the Acurex corporation could not able to raise its finances for implementing the project, which led to another agreement with LUZ corporation for establishing the first commercial parabolic trough plant in the world [55,60]. Luz Industries according to [71,74,216,217] constructed the first parabolic plant that was named SEGS I and operated it in 1984 and then after 1 year operated SEGE II. SEGE I and II were built at Daggett in Southern California about 155 miles northeast of Los Angeles [70]. As in [73–76], SEGS I and II are considered as the first stage in the development of solar trough technology, and in proving the commercial viability of this revolutionary technology. SEGS I was integrated with two storage tanks that were damaged by fire in 1999 and were not replaced, while SEGS II was combined with a natural gas fired Heat Transfer Fluid heater in order to provide electricity in cloudy days or after sunset [216,217]. According to [69,74–76], the main objectives of constructing SEGS I is to prove the ability of parabolic trough to generate electricity and examine the efficiency of the first type of heat collecting element (HCE) named LS1 (first Luz generation) that was installed at the SEGS I and then at SEGS II plants. The ability of solar collector assembly LS1 to generate 30 MW in SEGS II encouraged Luz to make significant improvement in the LS1 leading to the manufacture of LS2 (second Luz generation), which was used in SEGS III–VII power plants as stated in [74,76] that were built in the Mojave Desert at Kramer Junction, California because this location receives DNI resource 2940 kWh/m² yr better than Daggett location that receives 2792 kWh/m² yr [68,216–222]. Fig. 4 shows the SEGS plants in California, US.

In SEGS III, as per ([62] cited in [55]), [70,74,216–218], Luz examined the improved solar collector assembly LS2 and its ability to generate 30 MW with the same working fluid that was used in SEGS I and II. The improved collector succeeded in generating temperature higher than the generated temperature by LS1, which led to increase in the plant's efficiency from 29.4% to 30.6% and reduction in the cost of technology. The plant's solar field area and the temperature reached by the improved collector are shown in Table 1. This success encouraged Luz to continue in improving the solar collector assembly LS2 and building other plants in the same location. According to [74–76], the flux concentration of the LS2 assembly in 1988 was increased, which led to improvement in the efficiency of the technology. In 1989, SEGS IV–VII were operated,



Fig. 3. The first parabolic trough system in Maadi, Egypt [5] cited in [14].



Fig. 4. SEGS plants in California, US [19].

Table 1
Details of SEGS I–IX ([62] cited in [55]) [74,216–224].

SEGS plant	1st year of operation	Net output MWe	Collector type	Solar field outlet temp. (°C/°F)	Working fluid	Solar area (m ²)	Solar turbine EFF. (%)	Fossil turbine EFF. (%)	Annual output (MWh)	No. of storage units and its type	Storage capacity (h)	Note
I	1984	13.8	Luz LS-1	307/585	Therminol	82,960	31.5	–	30,100	2 (direct type)	3	Storage units were damaged by fire in 1999 and were not replaced
II	1985	30	Luz LS-1	316/601	Therminol	190,338	29.4	37.3	80,500	–	–	Hybrid with natural gas
III	1985	30	Luz LS-2	349/660	Therminol	230,300	30.6	37.4	92,780	–	–	Hybrid with natural gas
IV	1989	30	Luz LS-2	349/660	Therminol	230,300	30.6	37.4	92,780	–	–	Hybrid with natural gas
V	1989	30	Luz LS-2	349/660	Therminol	250,500	30.6	37.4	91,820	–	–	Hybrid with natural gas
VI	1989	30	Luz LS-2	390/734	Therminol	188,000	37.5	39.5	90,850	–	–	Hybrid with natural gas
VII	1989	30	Luz LS-2	390/734	Therminol	194,280	37.5	39.5	92,646	–	–	Hybrid with natural gas
VIII	1989	80	Luz LS-3	390/734	Therminol	464,340	37.6	37.6	252,750	–	–	Hybrid with natural gas
IX	1990	80	Luz LS-3	390/734	Therminol	483,960	37.6	37.6	256,125	–	–	Hybrid with natural gas

and each generated 30 MW [219–223]. The plants SEGS IV–V used the improved LS2 that produces heat at temperature 349 °C, while the plants SEGS VI–VII used the improved LS2 that produces heat at temperature 390 °C ([62,64] cited in [55]). As per [62] (cited in [55]) and [73–76], the plant's efficiency of SEGS VI–VII increased from 30.6% to 37.6% due to higher value of DNI in the plant's location and the significant improvement on LS2. According to [70,73–76,216–223], all SEGS plants except SEGS I has been hybridized with natural gas fired Heat Transfer Fluid heater (according to the U.S. regulations the allowed energy supplied by natural gas is limited to 25% of the total effective annual plant energy input) to achieve high capacity factor that leads to provide low-cost electricity and to serve the needs of the base and peak load. The plant operations are monitored and optimized constantly by customized computer controls [74].

As stated in [55,57,58], due to the ability of improved LS2 in increasing the efficiency of the plants, Luz in 1989 developed new solar collector assembly named LS3 (third Luz generation) to increase the flux concentration of the assembly higher than the improved LS2. They added that, the LS3 used in SEGS VIII and IX that were built at Harper Lake in San Bernadino County Southern California after PURPA allowed increasing the capacity of SEGS plants from 30 MW to 80 MW due to the success of the parabolic technology. In 1989 and 1990, SEGS VIII and IX, which are the largest solar power plants constructed by Luz Industries, were operated at a temperature of 390 °C (734 °F) [76,77]. The details of the largest SEGS plants (VIII and IX) are shown in Table 1 and the process diagram of SEGS VI is shown in Fig. 5

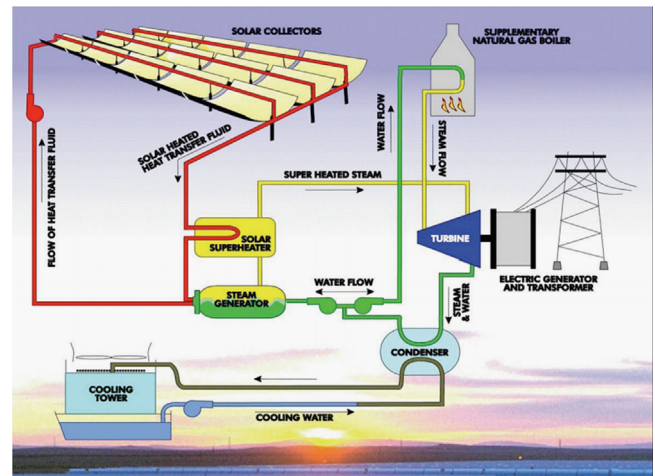


Fig. 5. Process diagram of SEGS VI [69].

Table 2

Characteristics of the three generations of Luz SCAs ([62,64] cited in [55]).

Collector	Luz LS-1	Luz LS-2	Luz LS-3	
Year	1984	1985	1988	1989
Area (m ²)	128	235	235	545
Aperture (m)	2.5	5	5	5.7
Length (m)	50	48	48	99
Receiver diameter (m)	0.042	0.07	0.07	0.07
Concentration ratio	61:1	71:1	71:1	82:1
Optical efficiency	0.737	0.737	0.764	0.8
Receiver absorptivity	0.94	0.94	0.99	0.96
Mirror reflectivity	0.94	0.94	0.94	0.94
Receiver emittance	0.3	0.24	0.19	0.19
At temperature (°C/°F)	300/572	300/572	350/662	350/662
Operative temp. (°C/°F)	307/585	349/660	390/734	390/734

Table 3

Gross solar production of electricity in MWh for the years 1985 to 2002 [67,72,74,75].

Plant	Year built	Location	Net turbine capacity (MW)	Gross solar production of electricity (MWh)								
				1985	1986	1987	1988	1989	1990	1991	1992	
SEGS I	1984	DLC	14	19,261	22,510	25,055	16,927	23,527	21,491	20,252	17,938	
SEGS II	1985	DLC	30		25,085	23,431	38,914	43,862	39,156	35,168	32,481	
SEGS III	1986	KJC	30			49,444	61,475	63,096	69,410	60,134	48,702	
SEGS IV	1986	KJC	30			52,181	64,762	70,552	74,661	64,600	51,007	
SEGS V	1987	KJC	30				62,858	65,280	72,449	59,009	55,383	
SEGS VI	1988	KJC	30					48,045	62,690	64,155	47,087	
SEGS VII	1988	KJC	30					38,868	57,661	58,373	46,940	
SEGS VIII	1989	HL	80						114,996	102,464	109,361	
SEGS IX	1990	HL	80						5974	144,805	129,558	
Total production (MWh)				19,261	47,595	150,111	244,937	353,230	518,487	608,960	538,458	
Plant	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	Average 1998–2002	Total
SEGS I	20,368	20,194	19,800	19,879	19,228	18,686	11,250	17,235	17,947	17,402	16,500	331,550
SEGS II	36,882	36,566	35,853	35,995	34,817	33,836	33,408	31,207	32,497	31,511	32,500	549,159
SEGS III	58,248	56,892	56,663	64,170	64,677	70,598	70,689	65,994	69,369	66,125	68,555	995,686
SEGS IV	58,935	57,795	54,929	61,970	64,503	71,635	71,142	63,457	64,842	70,313	68,278	1,017,283
SEGS V	67,685	66,255	63,757	71,439	75,936	75,229	70,293	73,810	71,826	73,235	72,879	1,014,444
SEGS VI	55,724	56,908	63,650	71,409	70,019	67,358	71,066	68,543	67,339	64,483	67,758	878,476
SEGS VII	54,110	53,251	61,220	70,138	69,186	67,651	66,258	64,195	64,210	62,196	65,048	834,986
SEGS VIII	130,999	134,578	133,843	139,174	136,410	137,905	135,233	140,079	137,754	138,977	137,990	1,691,773
SEGS IX	130,847	137,915	138,959	141,916	139,697	119,732	107,513	128,315	132,051	137,570	125,036	1,594,852
Total	613,798	620,358	628,674	676,091	674,473	662,631	636,851	652,835	657,834	662,542	654,539	8,967,123

According to [73], the main goal of building SEGS VIII and IX plants with size 2.67% to the previous fifth plants SEGS III–VII is to promote the commercialization of parabolic trough technology by increasing the overall conversion efficiency and decreasing the cost of kW generated by the technology. So to achieve this goal Luz Industries made a number of advancements, as a result of lessons gained from SEGS I–VII. The advances included (1) building the plants in location that has all success conditions of solar power generation such as high value of DNI, excellent water resources, relatively level land, proximity to electric transmissions facilities and natural gas lines, (2) increased the solar field's area to take the advantage of economies of scale, (3) Used the new solar collector assembly (LS3) to reduce the required number of tracking components and hence reduce the technology's cost, (4) Replaced the natural gas fired Heat Transfer Fluid heater with the natural gas boiler for supplying steam in the gas-fired mode of operation and (5) used reheat turbine cycle that increased the Rankine efficiency to 37.6% [70,74]. Tables 1 and 2 show the details of SEGS I–IX power plants.

As reported in [55,60,67,75], the success of the plants in achieving the main objectives of constructing them encouraged Luz Industries to construct the SEGS X, but because of the coinciding falling of fossil fuel prices with the withdrawal of tax credits and a change in the mandatory purchase contracts, Luz was declared bankrupt in 1991. They added that, Luz failed to operate the existing SEGS plants, which led him to sell the plants to a group of investors. SEGS I and II were sold and operated by the Dagget Leasing Corporation, SEGS III–VII were operated and managed by the Kramer Junction Company (KJC), and SEGS VIII and IX were run by the Harper Lake Company [67,78]. After that, Soler Solar Systems Ltd. who wholly own SEGS III–VII together with the operating company (KJC) as stated in [68], improved the efficiency of the SEGS plants significantly to make them competitive with fossil fuel plants. They introduced a collector tube named Universal Vacuum Collector (UVAC) in order to increase the efficiency of the solar field and hence reduce levelized cost of energy. The UVAC was tested in the field at SEGS VI, and it achieved excellent results with a 20% increase in the efficiency of the solar field on a yearly average and 30–35% reduction in LCOE from the original SEGS plants.

The parabolic trough technology employed in the first nine solar power plants in the world succeeded in proving the economic feasibility of its usage, where the SEGS I–IX are still in profitable commercial operation since its first operation year until

now with a history of increased efficiency and output as the operators improved their procedures. Table 3 and Fig. 6 show the gross solar production of electricity in MWh for the years 1985–2002.

As shown in Fig. 6 since 1990 the total production of the first nine PTC plants increased continuously in which the gross total solar production of electricity in 1990 was 518,487 MWh, while it reached to 662,542 MWh in 2002. This is due to the efficiencies of the SEGS III–VII plants that were improved by Soler Solar Systems Ltd. (Owner Company) and the KJC Company (Operating Company).

In 2003, Price et al. [68] evaluated the future cost and performance of parabolic trough plants on 30 MWe SEGS VI as reference plant because it is the last of the SEGS plants that uses the LS-2 collector for the full solar field, operates at the higher temperature and the operator company has provided detailed O&M data on this plant. They reported that, if the plant was built today based on the prices in 2002 the cost for (1) a solar-only PTC plant will be Capital cost 3008\$/kWe, O&M cost 0.046\$/kWh and LCOE 0.17\$/kWh, (2) a hybrid solar–natural gas (25%) plant will be Capital cost 3204\$/kWe, O&M cost 0.034\$/kWh, Fuel cost 0.013\$/kWh and LCOE 0.141\$/kWh. They added that, when solar field size was scaled up to 50 MWe and advance components of the technology (new Soler receiver, replacing flexible hoses and using ball-joint assemblies) were used the cost of technology will reduce to Capital cost 2745\$/kWe, O&M cost 0.024\$/kWh and LCOE 0.11\$/kWh for a solar-only plant and Capital cost 2939\$/kWe, O&M cost 0.018\$/kWh, fuel cost 0.096\$/kWh and LCOE 0.141\$/kWh for the hybrid solar–natural gas (25%) plant. They also reported that, when the plant was scaled up and the 12 h storage system was included the Capital cost and M&O cost to generate (1) 100 MWe are 3416\$/kWe and 0.010\$/kWh and (2) 400 MWe are 225\$/kWe and 0.006\$/kWh respectively.

In 2012, Fraunhofer institute for Solar Energy systems (ISE) [215] analyzed the LCOE for renewable energies. They analyzed LCOE for 100 MWe CSP plants at DNI of 2000 kWh/m² yr based on data of completed power plant projects with parabolic trough, linear Fresnel collector and tower technology in Spain and US such as SEGS plants, 50 MW-Andsol1-3 PTC-storage (8 h) plants in Spain, 100 MWe-Shams PTC-natural gas plant in Abu Dhabi, 20 MWe-Gemasolar tower with 15 h storage in Spain and 30 MWe-Puerto Errado2 LFC with buffer plant in Spain. The results showed that the LCOE for parabolic trough plant without storage is 0.265 euro/kWh and with storage is 0.187 euro/kWh, while for linear Fresnel collector with buffer and tower power with storage

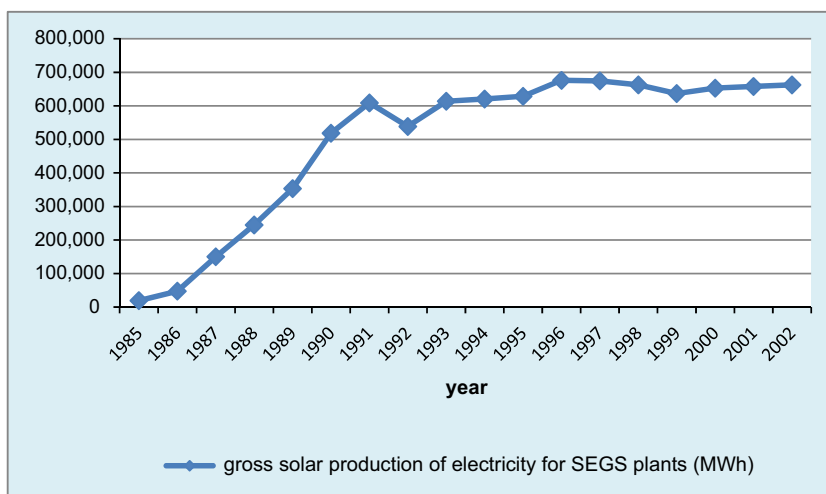


Fig. 6. Gross solar production of electricity in MWh for the years 1985–2002.

Table 4

Details of the operational, under construction and under development projects of parabolic trough collector worldwide.

Break ground Year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
–	Since 1984	SEGS I–IX	Luz	U.S.	Commercial	See Table 1	Totally 354 MW	Operational	[216–224]	See Table 1
2004	Jan. 2006	Saguaro	Arizona Public Service	Red Rock, Arizona, Pinal County, Southwest USA	Production	2636 kWh/m ² /yr	1.16 MW at 323.0 psi	Operational	[126]	
–	2008	Shiraz	–	Shiraz, Iran	–	100,000 m ² Xceltherm -600	572 °F	Operational	[140]	
Jan. 2006	Dec., 2009	Sopogy's Holaniku	Keahole Solar Power, LLC , Sopogy	Keahole Point, Hawaii, Hawaii,U.S.	Commercial	– Therminol VP-1	0.25 MW at 2 MW at	Operational	[128]	Storage system provide 2 h
Feb. 2006	June 2007	Nevada Solar One	Acciona Energía	Boulder City, Nevada, Clark, U.S.	Commercial	– Xceltherm-600	176 °C	Operational	[127]	It is the third largest CSP plant in the world and the first plant built in the United States since 1999.
July 3, 2006	Nov. 26, 2008	Andasol-1	ACS/Cobra Group	Aldiere, Granada, Spain	Commercial	357,200 m ² Dowtherm A	– 393 °C	Operational	[79]	Storage system provide 0.5 h
Jan. 1, 2007	Jan. 1, 2009	Solnova 1	Abengoa Solar	Sevilla, Sanlúcar la Mayor, Spain	Commercial	2136 kWh/m ² /yr	50 MW at	Operational	[80]	It is the first parabolic trough power plant in Europe and the first in the world with 2-tank indirect storage system provide 7.5 h.
Jan. 1, 2007	Jan. 1, 2009	Solnova 3	Abengoa Solar	Sevilla, Sanlúcar la Mayor, Spain	Commercial	510,120 m ² Dowtherm A	100 bar 393 °C	Operational	[81]	
Mar. 1, 2007	Jan. 1, 2009	Ibersol Ciudad Real (Puertollano)	Iberdrola Renovables	Puertollano, Castilla-La Mancha, Spain	Commercial	300,000 m ² Thermal oil	100 bar 393 °C	Operational	[82]	
Mar. 15, 2007	June 1, 2009	Andasol-2	ACS/Cobra Group	Aldeire y La Calahorra , Granada, Spain	Commercial	2061 kWh/m ² /yr	50 MW at	Operational	[84]	2-Tank indirect storage system provide 7.5 h
Oct. 2007	July 2011	ISCC Hassi R'mel	Abener	Hassi R'mel, Hassi R'mel, Algeria	Commercial	287,760 m ² Dowtherm A	100 bar 391 °C	Operational	[150]	The total plant capacity = 150 MWe (125 MWe combined fossil fuel cycle + 25 MWe solar input)
Dec. 2007	June, 2009	La Risca	Acciona Energía	Alvarado, Badajoz, Spain	Commercial	510,120 m ² Dowtherm A	100 bar 393 °C	Operational	[85]	
Jan. 1, 2008	Jan. 1, 2009	Solnova 4	Abengoa Solar	Sevilla, Sanlúcar la Mayor, Spain	Commercial	183,860 m ² Therminol oil	100 bar 393 °C	Operational	[83]	
						2174 kWh/m ² /yr	50 MW at			
						352,854 m ² Biphenyl/diphenyl oxide	100 bar 393 °C			
						2012 kWh/m ² /yr	50 MW at			
						300,000 m ² Thermal oil	100 bar 393 °C			

Table 4 (continued)

Break ground Year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
–	2009	ISCCS Yazd.	Iran Electricity Development Organization	KM 33 of Yazd-Khazarabad, Iran	Commercial	–	467 MW at 100 bar	Operational	[141]	Gas turbine = 2 × 115 MWe
March 1, 2008	August 2011	Andasol-3	Duro Felguera Group	Aldiere, Granada, Spain	Commercial	Therminol VP-1 2200 kWh/m ² /yr	50 MW at	Operational	[95]	Steam turbine = 200 MWe Solar input = 67 MWe [63] 2-Tank indirect storage system provide 7.5 h
April 2008	May, 2010	ISCC Ain Beni Mathar	Abener	Ain Beni Mathar, Ain Beni Mathar, Morocco	Commercial	–	100 bar 393 °C 20 MW at	Operational	[148]	The overall capacity = 470 MWe (450 MWe combined fossil fuel cycle + 20 MWe solar input).
July 1, 2008	June 1, 2010	La Florida	Renovables SAMCA	Badajoz, Badajoz, Spain	Commercial	–183,120 m ² Therminol VP-1	100 bar 393 °C 50 MW at	Operational	[87]	Storage system provide 7.5 h
July 21, 2008	July 14, 2010	Archimede	ENEL	Priolo Gargallo, Sicily, Italy	–	552,750 m ² Diphenyl/Biphenyl oxide 1936 kWh/m ² /yr	100 bar 393 °C 5 MW at	Operational	[125]	It is the first PTC use molten salt –HTF and 2-tank direct storage system provides 8 hours
July 2008	Feb. 2011	La Dehesa	Renovables SAMCA	La Garrovilla, Badajoz, Spain	Commercial	–	31,860 m ² Molten salt (60% NaNO ₂ , 40% KNO ₂) 50 MW at	93.83 bar 550 °C Operational	[92]	2-Tank indirect provide 7.5 h
Oct. 2008	Dec. ,2010	Palma del Río II	Acciona Energía	Palma del Río, Córdoba, Spain	Commercial	552,7 50 m ² Diphenyl/biphenyl oxide 2291 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[90]	
Oct. 2008	Jan. ,2011	Manchasol-1	ACS/Cobra Group	Alcazar de San Juan, Ciudad Real, Spain	Commercial	372,240 m ² Biphenyl/Diphenyl oxide 2208 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[91]	2-Tank indirect provide 7.5 h
Nov. 2008	Dec. 27, 2011	Lebrija 1	Soleval Renovables, S.L.	Lebrija, Sevilla, Spain	Commercial	510,120 m ² Diphenyl/Diphenyl oxide 1993 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[99]	
Jan. 2009	Dec. 2010	Martin Next Generation Solar Energy Center	Florida Power & Light Co.	Indiantown, Florida, Martin, South Florida, U.S.	Commercial	–	412,020 m ² Therminol VP1 75 MW	395 °C Operational	[129]	It is the second largest solar plant in the world and the largest solar plant of any kind outside of California.
Mar. 2009	Oct. 2010	Majadas I	Acciona Energía	Majadas de Tiétar, Cáceres, Spain	Commercial	464,908 m ² Dowtherm A 2142 kWh/m ² /yr	100 bar 372,240 m ²	Operational	[88]	(The PTC field hybrid with an existing combined-cycle power plant)

May 1, 2009	Sep. 1, 2011	Helioenergy 1	Abengoa Solar ; EON	Écija, Sevilla, Spain	Commercial	Biphenyl/Diphenyl oxide -	393 °C 50 MW at	Operational	[96]	
May 1, 2009	Dec. 1, 2011	Arcosol 50	Torresol	San José del Valle, Cádiz, Spain	Commercial	300,000 m ² Thermal Oil 2097 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[97]	2-Tank indirect provide 7.5 h
May 1, 2009	Dec. 1 2011	Termesol 50	Torresol	San José del Valle, Cádiz, Spain	Commercial	510,120 m ² Dowtherm A 2097 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[98]	2-Tank indirect provide 7.5 h
May 8, 2009	Aug. 1, 2012	Extresol-3	ACS/Cobra Group	Torre de Miguel Sesmero, Badajoz, Spain	Commercial	510,120 m ² Diphenyl/Diphenyl Oxide 2168 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[109]	2-Tank indirect provide 7.5 h
May 2009	April 2011	Manchasol-2	ACS/Cobra Group	Alcazar de San Juan, Ciudad Real, Spain	Commercial	510,120 m ² Diphenyl/Diphenyl oxide 2208 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[93]	2-Tank indirect provide 7.5 h
-	June 2011	ISCC Kuraymat	NREA	Kuraymat, 100 km south of Cairo, Egypt	Commercial	510,120 m ² Diphenyl/Diphenyl oxide 2431 kWh/m ² /yr	100 bar 393 °C 20 MW at	Operational	[149]	The total plant capacity = 140 MWe (120 MWe combined fossil fuel cycle + 20 MW solar input)
June 2009	July 2011	Palma del Río I	Acciona Energía	Palma del Río, Córdoba, Spain	Commercial	130,800 m ² Therminol VP-1 2291 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[94]	
Aug. 1, 2009	2010	Colorado	Xcel Energy ; Abengoa Solar	Palisade, Colorado, U.S.	Commercial	372,240 m ² Biphenyl/diphenyl oxide 6664 m ²	100 bar 393 °C 2 MW	Operational	[130]	It is hybrid CSP-fossil fuel (coal) plant
Oct. 3, 2009	Jan. 1, 2010	Extresol-1	ACS/Cobra Group	Torre de Miguel Sesmero, Badajoz, Spain	Commercial	Oil 2168 kWh/m ² /yr	(hybrid with existing cycle) 50 MW at	Operational	[86]	2-Tank indirect provide 7.5 h
Nov. 12, 2009	2010	Extresol-2	ACS/Cobra Group	Torre de Miguel Sesmero, Badajoz, Spain	Commercial	510,120 m ² Diphenyl/Biphenyl oxide 2168 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[89]	2-Tank indirect provide 7.5 h
-	Jan., 2012	Helioenergy 2	Abengoa	Écija, Sevilla, Spain	Commercial	510,120 m ² Diphenyl/Biphenyl oxide -	100 bar 393 °C 50 MW at	Operational	[100]	
-	Jan. 2012	Aste 1 A	EON Elecnor/Aries/ ABM AMRO	Alcázar de San Juan, Ciudad Real, Spain	Commercial	300,000 m ² Thermal Oil 2019 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[101]	2-Tank indirect provide 8 h
-	Jan. 2012	Aste 1B	Elecnor/Aries/ ABM AMRO	Alcázar de San Juan, Ciudad Real, Spain	Commercial	510,120 m ² Diphenyl/diphenyl oxide 2019 kWh/m ² /yr	100 bar 393 °C 50 MW at	Operational	[102]	2-Tank indirect provide 8 h
						510,120 m ² Diphenyl/Diphenyl Oxide	100 bar 393 °C			

Table 4 (continued)

Break ground Year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
–	Jan. 25, 2012	Thai Solar Energy 1	Solarlite GmbH	Huai Kachao, Kanchanaburi Province, Thailand	Commercial	–	5 MW at	Operational	[138]	It is the first commercial solar thermal power plant based on direct steam generation
–	Feb. 1, 2012	Solacor 1	Abengoa Solar	El Carpio, Córdoba, Spain	Commercial	45,000 m ² Water/ steam	30 bar 340 °C	Operational	[103]	
–	Mar. 9, 2012	Solacor 2	Abengoa Solar	El Carpio, Córdoba, Spain	Commercial	300,000 m ² Thermal Oil	100 bar 393 °C	Operational	[104]	
–	May 2012	Morón	Acciona/Seridom	Morón de la Frontera, Seville, Spain	Commercial	300,000 m ² Thermal Oil	100 bar 393 °C	Operational	[105]	
June 2010	June 2012	Helios 1	Helios I HYPERION Energy Investments, S. L.	Puerto Lápice, Ciudad Real, Spain	Commercial	380,000 m ² Thermal oil	100 bar 393 °C	Operational	[106]	
–	June 2012	Solaben 3	Abengoa Solar	Logrosán, Cáceres, Spain	Commercial	2217 kWh/m ² /yr	50 MW at	Operational	[107]	
July 2010	July 2012	Guzmán	FCC Energy	Palma del Río, Córdoba, Spain	Commercial	300,000 m ² Thermal oil	100 bar 393 °C	Operational	[108]	
July 2010	Mar. 17, 2013	Shams 1	Masdar/Total/Abengoa Solar	Madinat Zayed, 120 km southwest of Abu Dhabi, U.A. E.	Commercial	300,000 m ² Thermal Oil	100 bar 393 °C	Operational	[109]	
Aug. 2010	Aug., 2012	Helios 2	Helios II HYPERION Energy Investments, S. L.	Puerto Lápice, Ciudad Real, Spain	Commercial	–	50 MW at	Operational	[108]	
–	Aug. 2012	Orellana	Acciona	Orellana, Badajoz, Spain	Commercial	310,406 m ² Dowtherm A	100 bar 393 °C	Operational	[139]	It is the first commercial solar thermal power plant in Middle East.
–	Aug. 2012	Orellana	Acciona	Orellana, Badajoz, Spain	Commercial	627,840 m ² Therminol VP-1	100 bar 400 °C	Operational	[110]	Hybrid CSP-natural gas plant
Aug. 2010	Sep., 2012	Olivenza 1	Ibereco Solar	Olivenza, Badajoz, Spain	Commercial	2217 kWh/m ² /yr	50 MW at	Operational	[111]	
–	Oct., 2012	Solaben 2	Abengoa Solar	Logrosán, Cáceres, Spain	Commercial	300,000 m ² Thermal Oil	100 bar 393 °C	Operational	[112]	
–	Nov. 21, 2012	La Africana	Ortiz/TSK/Magtel	Posadas, Córdoba, Spain	Commercial	402,210 m ² Thermal Oil	100 bar 393 °C	Operational	[113]	
–	Nov. 21, 2012	La Africana	Ortiz/TSK/Magtel	Posadas, Córdoba, Spain	Commercial	300,000 m ² Thermal Oil	100 bar 393 °C	Operational	[114]	2-Tank indirect provide 7.5 h
Dec. 15, 2010	Jan. 2014	Genesis Solar Energy Project	ESA	Blythe, California, Riverside, U.S.	Commercial	1950 kWh/m ² /yr	50 MW at	Operational	[114]	
						550,000 m ² Thermal Oil	100 bar 393 °C	Under construction	[133]	The Project will include two 125-MW units
						Therminol VP-1	250 MW at 100 bar 740 °F			

Dec. 2010	Aug. 2013	Solana Generating Station	Abengoa Solar	Phoenix, Arizona, Maricopa, Gila Bend, U.S.	Commercial	– 2,200,000 m ² Therminol VP-1	280 MW at 100 bar 715 °F	Under construction	[132]	2-Tank indirect provide 6 h
March 2011	Dec. 2012	Borges Termosolar	Abantia	Les Borges Blanques, Lleida, Spain	Commercial	– 183,120 m ² Thermal Oil 2052 kWh/m ² /yr	25 MW at 100 bar 393 °C	Operational	[115]	Hybrid CSP-Biomass plant uses two biomass units each 22 MW
–	2012	Astexol II	Elecnor/Aries/ABM AMRO	Olivenza, Badajoz,Spain	Commercial	– 510,120 m ² Thermal Oil	50 MW at 100 bar 393 °C	Operational	[116]	2-Tank indirect provide 8 h
March 2011	Mar., 2013	Termosol 1	NextEra, FPL	Navalvillar de Pela, Badajoz, Spain	Commercial	– 523,200 m ² Thermal oil	50 MW at 100 bar 393 °C	Operational	[117]	2-Tank indirect provide 9 h
March 2011	Mar., 2013	Termosol 2	NextEra, FPL	Navalvillar de Pela, Badajoz, Spain	Commercial	– 523,200 m ² Thermal oil	50 MW at 100 bar 393 °C	Operational	[118]	2-Tank indirect provide 9 h
–	March 2013	Caceres	Cobra Instalaciones y Servicios	Valdeobispo, Caceres, Spain	Commercial	– 510,120 m ² Diphenyl/biphenyl oxide	50 MW at 100 bar 393 °C	Under construction	[119]	2-Tank indirect provide 7.5 h
August 2011	July 2013	Enerstar	FCC Energy	Villena, Alicante , Spain	Commercial	– 339,506 m ² Thermal oil	50 MW at 100 bar 393 °C	Under construction	[120]	
Aug. 2011	2014	Mojave Solar Plant	Abengoa Solar	Harper Dry Lake, California, San Bernardino, U.S.	Commercial	– Therminol VP-1	280 MW at 100 bar 50 MW at	Under construction	[134]	
Nov. 2011	Oct. 2013	Arenales	RREF/OHL	Morón de la Frontera, Sevilla , Spain	Commercial	– 510,120 m ² Thermal oil	50 MW at 100 bar 393 °C	Under construction	[121]	2-Tank indirect provide 7.5 h
Nov. 2011	April 2013	ISCC Agua Prieta II	Abengoa Solar	Agua Prieta, Sonora State, Mexico	Commercial	– 85,000 m ² Thermal oil	14 MW at 100 bar 50 MW at	Under construction	[131]	The overall capacity =478 MW (464 MW combined cycle+ 14 MW solar input or an additional natural gas duct–burner allows a similar production of 14 MWe when solar field is not in operation.
Nov. 2011	March 2013	Godawari Solar Project	Godawari Green Energy Limited	Naukh, Rajasthan, India	Commercial	– 392400 m ² Dow chemical	100 bar 390 °C	Under construction	[144]	
Dec. 2011	March 2013	Megha Solar Plant	Megha Engineering and Infrastructure	Anantapur, Andhra Pradesh, India	Commercial	– 366,240 m ² Synthetic oil	50 MW at 100 bar 393 °C	Under construction	[146]	
–	March 2013	Nokh	Ener-t International Ltd.	Rajasthan, Jaisalmer, India	Commercial	– – Therminol VP-1	50 MW at 100 bar 393 °C	Under construction	[142]	
–	March 2013	Or Abhijeet Solar Project Diwakar Solar Project	Lanco Solar	Askandra, Rajasthan, India	Commercial	– – Synthetic oil	100 MW at 100 bar 393 °C	Under construction	[145]	2-Tank indirect provide 4 h

Table 4 (continued)

Break ground Year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
–	March 2013	KVK Energy Solar Project	KVK Energy Ventures Ltd	Askandra, Rajasthan, India	Commercial	–	100 MW at 100 bar	Under construction	[147]	2-Tank indirect provide 4 h
2011	2013	Victorville 2	Inland Energy, Inc	Victorville, California, U.S.	Commercial	– Synthetic oil	50 MW at 393 °C	Under development	[135]	Hybrid power plant
2011	2013	Palmade Hybrid Power Plant	Inland Energy, Inc	Victorville, California, U.S.	Commercial	– Therminol VP-1	100 bar 50 MW at 393 °C	Under development	[136]	(50 MW solar input+513 MW natural gas) Hybrid power plant
2011	2014	NextEra Beacon	NextEra Energy	California City, California, Kern, U.S.	Commercial	– Therminol VP-1	100 bar 250 MW at 393 °C	Under development	[137]	(50 MW solar input+520 MW natural gas)
–	2013	Solaben 1	Abengoa Solar	Logrosán, Cáceres , Spain	Commercial	– Therminol VP-1	100 bar 50 MW at 393 °C	Under construction	[122]	
–	2013	Solaben 6	Abengoa Solar	Logrosán, Cáceres , Spain	Commercial	– 300,000 m ² Thermal oil	100 bar 50 MW at 393 °C	Under construction	[123]	
–	2013	Casablanca	COBRA	Talarrubias, Badajoz , Spain	Commercial	– 300,000 m ² Thermal oil	100 bar 50 MW at 393 °C	Under construction	[124]	2-Tank indirect provide 7.5 h
–	2013	Gujarat Solar One	Cargo Solar Power	Kutch, Gujarat, India	Commercial	– 510,120 m ² Diphenyl/biphenyl oxide	100 bar 393 °C	Under construction	[143]	2-Tank indirect provide 9 h
Feb. 2012	August 2013	Airlight Energy Ait Baha Plant	Airlight Energy	Ait Baha, Agadir, Morocco	Commercial	– Diphy 2,400 kWh/m ² /yr	100 bar 393 °C 3 MW at	Under construction	[151]	“The Solar field is designed to recover waste heat from the cement factory and provide additional heat at higher temperature to the existing 12 MW ORC Generator”[151]
Oct. 2012	2015	Pedro de Valdivia	Grupo Ibereolica	Maria Elena, Antofagasta, Chile	Commercial	– 6159 m ² Air at ambient pressure	100 bar 650 °C	Under construction	[155]	Storage system provide 12 h
Nov. 2012	June 2014	KaXu Solar One	Abengoa Solar	Poffader, Northern Cape, South Africa	Commercial	– kWh/m ² /yr	360 MW at 100 bar 393 °C	Under construction	[153]	Plant consists of two phases (I and II) each phase includes 2 × 90 MW units Storage system: 2-Tank indirect provide 10.5 h 2-Tank indirect provide 3 h
Dec. 2012	2015	Ouarzazate (Phase I)	ACWA, Aries and TSK	Ouarzazate, Morocco	Commercial	– 800,000 m ² – Therminol VP-1 2635 kWh/m ² /yr	100 bar 393 °C 160 MW at 100 bar	Under construction	[152]	2-Tank indirect provide 3 h
2013	2015	Bokpoort	ACWA	Globershoop, Northern Cape Province, South Africa	Commercial	– kWh/m ² /yr	50 MW at		[154]	2-Tank indirect provide 9 h

is 0.230 euro/kWh each. In addition, they studied the effect of DNI on LCOE by analyzing the LCOE for the CSP plants at DNI of 2500 kWh/m² yr, the LCOE for PTC without storage is 0.210 euro/kWh and with storage is 0.163 euro/kWh, while for LFC and Tower power with storage is 0.200 euro/kWh each respectively. So, from these two studies we can conclude that, PTC technology is considered the lowest cost large-scale solar power technology available today.

Currently, since parabolic trough technology has the lowest LCOE and a high maturity level with peak solar to electricity conversion efficiency, annual solar-to-electricity conversion, water consumption for cooling purposes and land use of 23–27%, 15–16%, 3–4/0.2 m³/MWh and 6–8 m³/MWh/a respectively [59], the developers of the technology have studied the opportunities to improve the output temperature and the overall efficiency of the solar field in order to increase the efficiency of Rankine cycle by finding alternatives for the heat transfer fluid instead of using oil as HTF [204].

3.2. Current projects

The continuous increase in the efficiency of parabolic trough technology in SEGS power plants in California has encouraged many countries especially Spain to utilize this technology for generating clean, reliable energy through constructing small or large scale solar plants. Details of the operation, under construction and under development projects of parabolic trough collector worldwide are shown in Table 4. It shows that the PTC technology is mature and is a commercially proven technology because it is still in operation in several commercial projects for approximately more than 28 years. Besides that, it shows that the possibility of hybridization of the PTC solar field with a new or an existing fossil fuel cycle or/and integrating it with storage system.

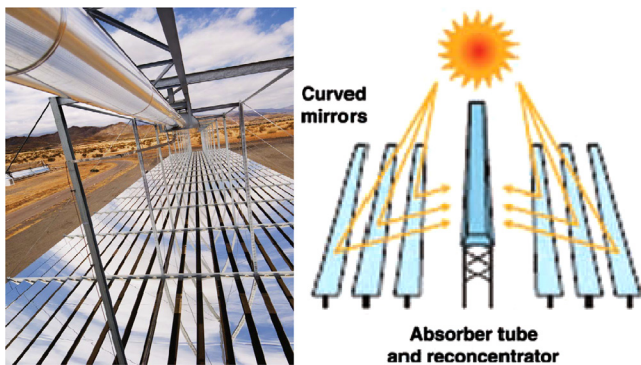


Fig. 7. Classical linear Fresnel collector [19,59].

4. Linear Fresnel collector technology (LFC)

LFC is one axis tracking technology, which consists of fixed collector and elevated inverted linear fixed receivers [17–24]. The collector is a parabola made up of 10 flat ground mounted mirrors, which each rotates according to sun's position for reflecting and concentrating the DNI of sun's energy onto linear receivers, which consist of a long, selectively coated absorber tube [17]. The advantages of using fixed receiver are the flexible connections required for the piping system that do not necessitate as in the case of the receivers used in parabolic trough collectors, which is considered the technically challenging and maintenance intensive for the PTCs [21], and the selection of heat transfer fluid (HTF) becomes more flexible because the fixed receiver can easily accommodate with various types of HTFs such as thermal oil, water or molten salt [22,23]. When the working fluid is water, the concentrated heat converts it at 50 times the atmospheric pressure into saturated steam at 250 °C directly in the receiver tube without the need of heat exchanger; this advantage leads to market the linear Fresnel technology using water as heat transfer fluid more than the other fluid. Fig. 7 shows the linear Fresnel collector technology.

It uses line focus technique similar to parabolic trough technology with lower capital costs due to light structural support, flat reflectors and fixed receiver without moving joints [2,16] and lower optical efficiency due to (1) higher cosine losses because of blocking of reflected solar radiation by adjacent mirrors and shading of incoming solar radiation at low sun positions, (2) mirrors on horizontal plane cannot reach ideal parabola and (3) shading by the fixed receiver [20,21]. However, it offers the promise of cost savings and reduced land use [21] by developing an advanced collector called Compact Linear Fresnel reflector, which provides the means for much more densely packed arrays [30]. The differences between LFC and PTC technologies are shown in Table 5.

4.1. Historical development

Baum et al. in 1957 developed the principle of the linear Fresnel collector (LFC) then in 1961, Giorgio Francia who is an Italian Mathematician and who designed both linear and two-axis tracking Fresnel reflectors applied the technology [26–28,30]. Then after 2 years, Francia designed and built the first LFC prototype at Lacédémone–Marseilles solar station [30]. After that in 1964, Francia tested the LFC prototype, which generated hourly steam at 100 atmospheric pressure and 450 °C equal to 38 kg [12,30]. Fig. 8 shows photos of Francia's first LFC prototype at Lacédémone–Marseilles solar station.

American corporation FMC, which was initiated during the oil crisis in 1979 according to [29,30], carried out in the late 1970s a development on linear Fresnel systems to develop large scale LFC

Table 5
Comparison between PTC and LFC technologies [22–24].

Component	Parabolic trough technology	LinearFresnel technology
Mirrors	Parabolic shape	Flat ground mounted (standardize mass produced)
Receiver	Moves with the entire trough system around the center of mass	Fixes and separates from reflector system
Support structure	Heavy	Light
Piping system	Need flexible connections	Don't need
On-site installation of	Takes long time	Faster and easier
Wind loads on collector	High	Low
Mirror surface per receiver	Lower than in LFCs	Higher than in PTCs.
Optical efficiency	High	Low
Land use	High	Low

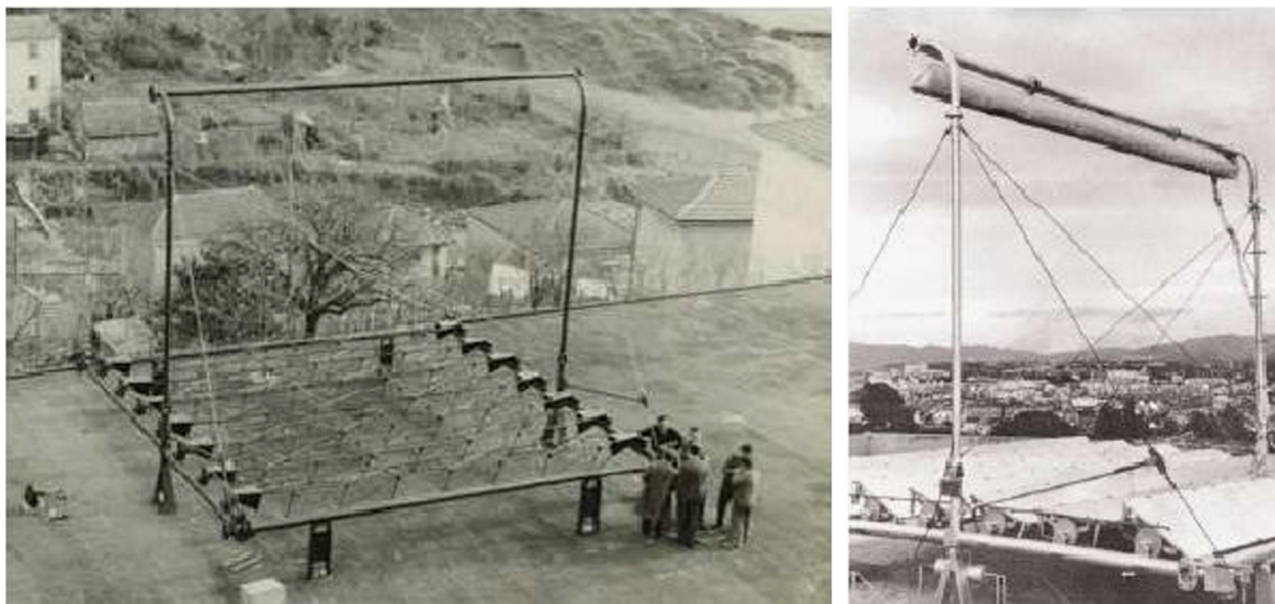


Fig. 8. Photos of Francia's first LFC prototype at Lacédémone–Marseilles solar station [12,30].

power plant that generates 10 MWe and 100 MWe; the first components for these plants were tested but due to lack of funding the work was stopped. The technology's proponents claimed that the effectiveness cost of the systems would have been better than the Power Tower systems under parallel development at the time [30]. As in [31], Israeli Paz Company in 1991 built a linear Fresnel collector at the Ben Gurion Solar Electricity Technologies Test Centre. The results of the test showed very low optical efficiencies due to construction difficulties such as shading and blocking effects. According to [35], the shading effect between the adjacent flat mirrors can be reduced by increasing the spacing between the mirrors within the collector, and the blocking effect can be reduced by increasing the height of the receiver tower, but these solutions will lead to increase in the capital cost of the classical technology.

At University of Sydney in 1993 according to [32,33], an advanced prototype of linear Fresnel collector was designed and named Compact Linear Fresnel Collector (CLFC) or (CLFR). It includes as stated in [30–33] of two receiver towers to collect the reflecting sun's rays from interleaving mirrors. Because in case of large scale plants there will be more than one fixed linear receiver in the plant and if they are close enough the interleaving mirrors within the fixed collector will have the possibility to reflect DNI to at least 2 receivers, which lead to much more densely packed arrays that lead to reduced shading and blocking effects and hence improve the optical efficiency of the technology as in [30]. Fig. 9 shows the advanced design of LFC that was patented in 1995 [32,28].

Austa Energy and Stanwell Corporation, Solahart International, Solsearch Pty. Ltd. in 1999 agreed to build the first CLFC plant at Stanwell Power Station near Rockhampton in Queensland, Australia under the Australian Greenhouse Renewable Energy Showcase scheme due to rise in the interest within the Australian utility industry, and to reduce the use of coal in the generation of electricity but after short time the Austa activities were canceled resulting in losing the developmental expertise of Austa for constructing the plant [33]. According to [30], Stanwell Corporation worked together with the Universities of Sydney and New South Wales to commercialize the advanced LFC technology by building solar thermal power plant that generates 14 MWe attached to a 1440 MWe coal fired power station owned by SCL

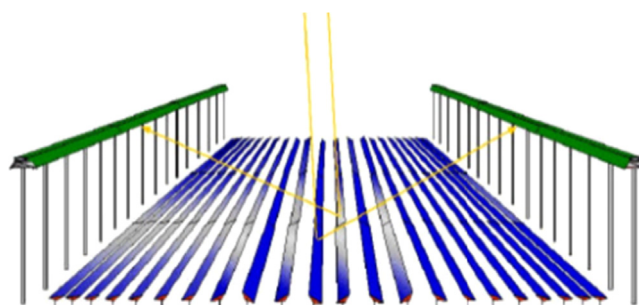


Fig. 9. Advance design of LFC [30].



Fig. 10. Stanwell power station near Rockhampton in Queensland, Australia [30].

as shown in Fig. 10. They stated that, the Stanwell solar plant uses water as heat transfer fluid and solar field aperture area of approximately more than 17,000 m² to preheat the feed water delivered to power cycle of the existing coal plant. The CLFC solar plant as stated in the same article produces steam at higher temperature of 265 °C, 5 MPa that is used for the re-heat stage of the steam cycle.

Table 6
Current projects of linear Fresnel collector worldwide.

Break ground year	Start production year	Project name	Company	Location/country	Project type	Solar resource , field area and HTF	Capacity	Status	Source	Note
–	–	CLFR plant beside Stanwell power station	Stanwell Corporation	Australia	Commercial	–	14 MW	Operational	[30]	Solar hybrid solar-existing coal power
March 14, 2008	March 19, 2009	Puerto Errado 1 Thermosolar	Novatec Solar España	Murcia, Calasparra, Spain	Prototype	2100 kWh/m ² /yr – Water	1.4 MW at 55 bar 270 °C	Operational	[50]	With single-tank thermocline
March 2008	October 2008	Kimberlina	Austa Energy	Bakersfield, CA, U.S.	Demonstration	– 25,988 m ² Water	5.0 MW at 40 bar	Operational	[46]	The first CLFR plant in North America
2011	2012	Augustin Fresnel 1	Solar Euromed	Targassonne, Pyreneans South of France	Prototype	1800 kWh/m ² /yr 400 m ² Water	0.25 MW at 65 bar, 300 °C	Operational	[43]	
January 2011	October 2012	Liddell	Novatec Solar	New South Walles, Liddell, Australia	Commercial	– 18,490 m ² Water	9.0 MW at 55 bar 270 °C	Operational	[48]	Solar hybrid solar-existing coal power
April 10, 2011	March 31, 2012	Puerto Errado 2 Thermosolar	Novatec Solar España	Murcia, Calasparra, Spain	Commercial	2095 kWh/m ² /yr 302,000 m ² Water	30 MW at 55 bar, 270 °C	Operational	[51]	Single-tank thermocline
June 2011	2013	Kogan Creek Solar Boost	CS Energy	Queensland , Chinchilla, Australia	Commercial	– – Water	44 MW at 60 bar 370 °C	Under construction	[47]	The largest solar hybrid solar-existing coal power station in the world
2011	2013	Dhursar	Rajasthan sun technique energy	Dhursar, Rajasthan, India	Commercial	–	100 MW	Under construction	[44]	
2013	2014	eCare	CNIM	Morocco	Demonstration	2600 kWh/m ² /yr 10,000 m ² Water	1.0 MW at 70 bar, 280 °C	Under construction	[45]	
–	2014	Alba Nova 1	Solar Euromed	Ghisonaccia, Corsica, France	Demonstration	1800 kWh/m ² /yr 140,000 m ² Water	12MW at 65 bar, 300 °C	Under construction	[42]	The first plant in France
2014	2015	Llo	CNIM	Pyrénées Orientales, Llo, France	Commercial	1930 kWh/m ² /yr 120,000 m ² Water	9.0 MW at 70 bar 285 °C	Under construction	[49]	

Belgian company Solarmundo in 2001, according to [36,37], built a 2500 m² prototype in Liège, Belgium. The general idea of this prototype is not new, but the company attracted attention with their concept of a Fresnel collector that claims to be more cost effective than the existing solar thermal technologies. In 2004, according to [38–40], Solarmundo merged with the Solar Power Group, Germany, who constructed a large pilot LFC system at the Plataforma Solar de Almería (PSA) in Spain named Fresdemo, which was tested until 2008. Since 2005 several linear Fresnel collectors have been built for industrial process heat applications and solar cooling in various locations across the United States according to [41].

Currently, a simple design has been evolved using an advanced cavity receiver [37]. However, the progress of linear Fresnel technology to improve its optical efficiency, cost of generated kWh, and land use is slow but it is steady technically and very efficient. It is still in the experimental stage, and it is considered a direct competitor for parabolic trough technology if its optical efficiency is improved, so the manufacturing companies that are working in this field should carry out development work to make it competitive with its direct competitor and to promote the commercialization of technology by overcoming its drawbacks. The technology's peak solar to electricity conversion efficiency, annual solar-to-electricity conversion, water consumption for cooling purposes and land use as stated in [59] reached to 18–22%, 8–10%, 3–4/0.2 m³/MWh and 4–6 m³/MWh/a respectively.

4.2. Current projects

LFC technology has been used to operate or construct solar projects worldwide; few and most of them are either prototypes or demonstration projects generated by few MWe to prove that the technology is technically and commercially viable, and its ability to integrate it with fossil fuel or storage system. Table 6 shows details of the operational, under construction and under development projects of LFC worldwide.

5. Tower solar power (TSP)

It is known also as central receiver technology. It is two axes tracking technology, and it comprises of a number of circular arrays [17]. The array is a number of fixed, flat (or slightly bended) heliostats. The heliostat is a million of sun-tracking mirrors, which reflect the DNI of sun's ray to a central receiver at the top of a power tower to produce high temperature heat [18]. This heat is absorbed by the transfer medium, which is used to produce superheated steam. Then the super-heated steam utilizes in the Rankine cycle to drive conventional generator [2,16]. Fig.11 shows the tower solar power technology, which uses the point focus technique to concentrate the sun heat.

The technology solar field has three configurations according to the arrangement of heliostats with the receiver system. In the first configuration, the receiver is a vertical plane with a north-facing heat transfer surface, and the collectors are located in the northern hemisphere of the tower. In the second configuration, the receiver is cylindrical with an exterior heat transfer surface, and the collectors are located around the tower (circle configuration). In the third configuration, the receiver has an enclosed heat transfer surface, and the collectors are located north of the receiver. The aim of these configurations is to reduce the blocking and shading effects of the heliostats in order to improve the optical efficiency and hence reduce the solar field cost. In general, the central receiver technology is preferred to be used for large scale utility power plants that reach hundreds of MWe because it needs large scale receiver and high number of expensive heliostats and hence

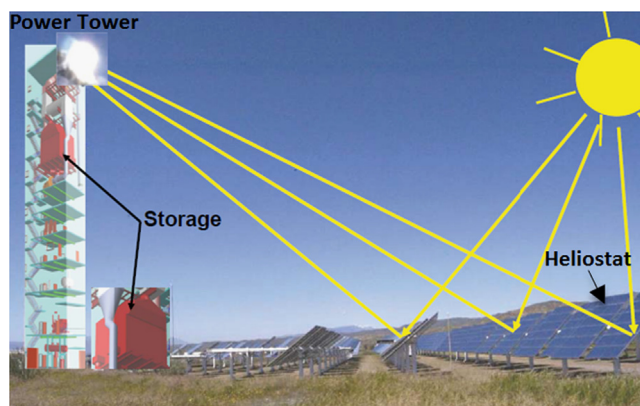


Fig. 11. Tower solar power technology [59].

large amount of space more than other CSP technologies to concentrate the sun's heat. The amount of space required is around 4.6 m²/MWh/yr [205].

The tower technology considered has a large potential for mid-term cost reduction of the generated electricity compared to PTC technology because the receiver can be operated with different heat transfer fluids such as molten salt, open air, superheated steam, pressurized air and solar fuels. These alternative fluids will produce concentrated heat temperature higher than the temperature that is produced in the commercial plant PS10, which uses water/steam HTF that produces heat temperature ranging 250–300 °C. Molten salt heat transfer fluid was demonstrated by Solar Two plant, and it presented a significant improvement on the plant efficiency and hence the technology cost [205]. The main advantage of using molten salt HTF is it can be used as transfer medium and storage medium at temperatures up to 565 °C, which makes this technology a better energy storage capacity among all CSP technologies [204] and the main disadvantage is that the water consumption for cleaning the heliostats and for cooling the exhaust wet steam from turbine is higher than the other solar technologies.

5.1. Historical development

In 1976, according to [200–202], the Commission of the European Communities (CEC) decided to demonstrate the effectiveness of tower power technology to convert the sun's rays into electricity through building the first power plant in the megawatt range because of the importance of generating clean electricity in European communities by using solar energy. The plant as stated in [6,156] was named EURELIOS and located in a large valley, about 30 km from sea in Adriano, Sicily, Italy. In the same year, an international industrial consortium that consisted of ANSALDO S. P.A. and Ente Nazionale per l'Energia Elettrica (ENEL), Italy; CETHEL (Combining Renault, Five- Cail- Babcock, Saint- Gobain Ponta-Mousson and Heurtey S.A.), France and Messerschmitt-Bölkow-Blohm (MBB), Federal Republic of Germany began construction of the plant [6]. By Nov. 1978, these firms completed the construction and testing of prototype models and by the end of 1980, all construction of EURELIOS was completed and connected to the grid of Italian National Electricity Board (ENEL), which was the operator of the plant and together with the CEC, its co-proprietor [6,156]. Fig. 12 shows photo of Eurelios plant.

As per [6,156], the EURELIOS consisted of 6200 m² of mirror surface, which was mounted on 182 two axes tracked heliostats placed within two subfields divided by a north–south line in order to test under field conditions, receiver located at the top of 55 m high tower and a thermal buffer to allow the plant to operate for 30 min at decelerated power when clouds pass over the heliostat

field, in order to protect the turbine against thermal shocks caused by inducing rapid variations of the DNI on the boiler. They stated that, at that time using storage units were not foreseen. The working fluid used to produce steam was water. MBB and CETHEL developed the heliostats and ANSALDO developed the receiver according to the results and experience of Francia [6]. ANSALDO's receiver consisted of two parallel finned, darkened surface tubes to increase the efficiency of DNI absorption, rolled up in a coil to form the walls of an open conical cavity-type boiler in which the DNI was focused and absorbed by working fluid, and the receiver was equipped with Pyrex sheets located on the inside of the tube in order to reduce the thermal energy loss due to infrared radiation and convection and transparent only to the incident radiation as in [6]. Table 7 shows the characteristics of the heliostats that were used in EURELIOS.

As per [156], the plant according to the analytical study of solar-radiation characteristics at EURELIOS power plant of Adrano that was carried out under contract with the Italian Electricity Board (ENEL) during 2 years (Jun 1978–Jun 1980) succeeded to generate 4 Kwh/m² in winter season, 5 kwh/m² in spring season and 7 kwh/m² in summer season with overall conversion efficiency equal to 16%, but the cost was prohibitive. The lessons got from this experimental plant were the plant conversion efficiency must increase and the heliostat cost must decrease by decreasing the size of the mirror that represents 50–30% of the total plant investment costs [6,156] and the hybridization of the plant with fossil fuels might increase the overall conversion efficiency to 35% [6]. These lessons were realized by DOE, who started in the late 1970s to obtain the best heliostat design to establish the first large scale tower plant in the world with storage unit. The plant was named Solar One and designed by Department of Energy (DOE), Southern California Edison, LA Dept. of Water and Power, and California Energy Commission to generate 10 MWe.

In 1981, according to [171,205], the plant was built and it consisted of 1818 mirrors, each 40 m² (430 ft²) with a total solar field area of 72,650 m² (782,000 ft²) and oil/rock thermal storage that was used to increase the generating power capability of the plant and to provide steam at low temperature for keeping the plant's parts warm during the off-hours and at starting time in the morning. Water/steam was used as working fluid. In 1982, the plant was operated for next 6 years and during these years the operating time reached to 8 h in summer days and 4 h in winter days [157,171] with the annual efficiency reaching up to 7% only due to the lack of dispatchability of electricity, thermal shocks of the turbine each time clouds pass over the heliostat and the complexity of oil/rock thermal storage that caused high thermodynamic losses [158–160].

In 1988, the Solar One was decommissioned [157,171], but during its operating years the U.S. Department of Energy (DOE) and industry tried to eliminate the disadvantages of Solar One through funding a series of researches on changing the receiver working fluid [161–164]. The best research's result was using a

60% sodium nitrate, 40% potassium nitrate molten salt receiver, which has lower operating pressure and higher allowing incident flux. As in [183], the effectiveness of the molten salt system was demonstrated by DOE, Sandia National Laboratories, and industry. They tested two 5 MWth receivers, one 7 Whth thermal storage system, one 3 MWth steam generator, one pump and valve loop sized for a 190 MWth receiver, and a series of panel and flow tests to qualify valves and freeze mitigation procedures [164–166] to construct small project consisting of one of the tested receivers, the thermal storage tanks, the steam generator, and one 750 kW turbine-generator to form a complete nitrate salt system [167]. The small project succeeded in demonstrating the effectiveness of the molten salt system in isolating the turbine/generator from receiver and hence the generator was not immediately affected by clouds or high wind speeds, and in eliminating the complexity of storage unit and hence allowed to store the excess energy, which led to increase in the efficiency of the plant [183]. Besides that, DOE realized that to commercialize the technology the plant should scale up and hybridize with fossil fuel or storage system to reduce technical and economic risks associated with the Solar One [169,171,183].

In 1996, DOE and Solar Two consortium, which consisted of Arizona Public Service Company, Bechtel Corporation, California Energy Commission, Electric Power Research Institute, Idaho Power Company, Los Angeles Department of Water and Power, PacifiCorp, Sacramento Municipal Utility District, Salt River Project and Southern California Edison Company [174], constructed the Solar Two power tower by adding 108 heliostats each of 95 m² with aperture area 10,200 m², a nitrate salt receiver (43 MWth), the salt storage system (3 h,105 MWth), salt steam generator



Fig. 12. Photo of Eurelios plant [66].

Table 7

Characteristics of the two heliostats [6].

Parameters of heliostats	MBB	CETHEL
Reflecting surface	23.0 m ²	51.8 m ²
Reflectivity	85%	80%
Mirror elements	16 elements (1.2 × 1.2 m ²)	48 elements (1.8 × 0.6 m ²)
Stowage positions	Focusing type 3-mm sandwich structure	Focusing type 6 mm flat glass
Tracking axes	Mirrors horizontal face down	Mirrors horizontal face down
Overall height	Horizontal/vertical	Horizontal/vertical
Overall width	4.48 m	7.87 m
Height of elevation (axis above ground)	5.60 m	8.84 m
Weight (excluding) foundation	2.95 m	4.2 m
	1500 kg	4900 kg

(35 MWth), and a new master control system to the existing components of Solar One [183]. The added heliostats were not new. They were salvaged from decommissioned photovoltaic facilities, and located to the south side of the existing collector field as stated in [183]. The total aperture area of the plant reached to 82,750 m² (891,000 ft²). Fig. 13 shows photo of Solar Two power plant—near Barstow, California. The plant according to [183] was directed by a Steering Committee headed by Southern California Edison and Technical Advisory Committee headed by Sandia. Steering Committee set project policy and objectives and it assured the accomplishment of project objectives as permitted by the project resources. Technical Advisory Committee reviewed the designs and the proposals and it supported transfer of information to all participants and Commercialization Advisory Board headed by Bechtel worked to use Solar Two as the stepping stone for the commercialization of power tower plants as stated in [183]. During construction of the project Sandia National Laboratories provided the necessary technical support [58,63].

The plant was operated in June 1996 with two storage tanks of 3 h storage capacity, and it generated 10 MWe through pumping



Fig. 13. Photo of Solar Two—near Barstow, California [19].

the molten salt stored in a cold storage tank at 554 °F (290 °C) by two multistage, vertical turbine pumps from the receiver sump to the receiver where it is heated to about 1050 °F (565 °C) by reflected sunlight from heliostats. Then the heated salt moves on to the hot storage tank by gravity [183]. For generating electricity the heated salt that was stored in hot storage tank is pumped by two vertical cantilever pumps from the steam generator sump to the steam generator for producing superheated steam at 512 °C/ 6.8-MPa [8,183]. Then steam was used to drive the turbine/generator system. To complete the cycle, salt outside from the steam generators was returned by gravity to cold storage tank to use it again as stated in [8,183]. Fig. 14 shows the principle of operation of Solar Two power plant. To avoid freezing of salt at 240 °C in the pipe or components Electric Heat Tracing (EHT) system was used. The output power of Solar Two is connected to 33 kV distribution network through 13.8/33 kV power transformer [171–173]. The nitrate salt thermal storage tanks utilized the air to passively cool the foundations to meet soil load-bearing constraints.

Solar Two was operated for 3 years, and during this period the plant succeeded in demonstrating the possibility of using molten salt as heat transfer fluid and as heat storage media, the decoupling of solar energy collection from electric energy generation, the potential to meet a utility evening peak demand, and the dispatch characteristics of a commercial plant [172,173]. During the first 2 years, the availability of the plant reached to above 80%, while in its last year under Southern California Edison (SCE) reached to 96% [159]. But the predicted energy cost of commercial plant was not achieved because of the high value of optical and thermal losses of the receiver [183]. In 1999, the Solar Two plant was decommissioned [8,183].

Success of Solar Two encouraged two of the project's key industry partners to pursue commercial molten salt receiver tower plant opportunities in Spain. The Spanish project was named "Solar Tres" or "Solar Three" because the capacity of the new constructed plant is three times larger than Solar Two. Initially, Solar Tres was promoted by the Spanish company GHERSA in association with NEXANT and based in the Boeing receiver technology. In 2001, SENER joined the team, but for different reasons NEXANT and Boeing left the project at that time; SENER

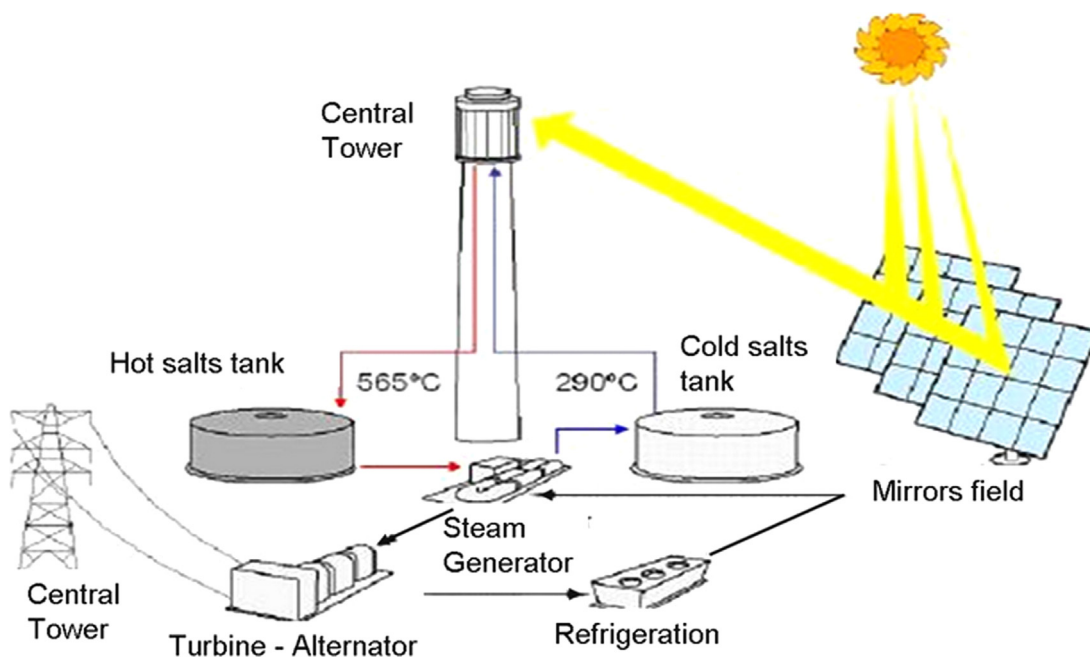


Fig. 14. Principle of operation Solar Two power plant [19].



Fig. 15. Photo of Solar Tres (GEMASOLAR) in Sevilla, Spain [59,19].



took over promotion of the project [176,179]. The project was funded by EU 5th Frame Program (SENER, GHERSA, Siemens and Saint Gobain) [179]. Fig. 15 shows the concentrating solar power tower system, Solar Tres, in Sevilla, Spain.

In mid of 2005, as in [177,178,180–182], SENER and CIEMAT joined forces to develop new receiver that has (1) flux surface which reaches to 1.0 MW/m^2 instead of 0.83 MW/m^2 at the receiver surface used in Solar Two in order to maximize the thermal efficiency, (2) small size to minimize the thermal losses in the plant, (3) small diameter to maximize the thermal efficiency and to prevent fatigue–creep damage and (4) excellent materials to guarantee excellent durability to reach 25 years at higher fluxes than previously experienced. The new receiver named SENER prototype was designed according to lessons learned from Solar Two and the wide experience of SENER & CIEMAT in tower and parabolic technologies [175]. In the end of 2006, the testing campaign was started by testing the materials that will be used for reproducing the prototype receiver to surpass the operating conditions in Solar Tres with respect to Solar Two power plant. The materials tests were carried out at CIEMAT laboratories. Besides that, in 2007, SENER developed a panel testing program in PSA to test the ability of an improved molten salt based-receiver to peak up maximum flux helping in reducing the cost of technology. The initial results of prototype receiver were excellent, and show that the improved receiver can fulfill the objectives of its design [176], which are (1) generate thermal power in salts much higher than the generated thermal power in Solar Two, (2) reduce the cost of technology and (3) improve the plant availability.

In 2009, as in [176], Torresol Energy's (60% SENER and 40% Masdar) under the supervision of SENER Company started to build the first commercial tower power plant in Fuentes de Andalucía, Sevilla, Spain with total reflective area equal to $310,000 \text{ m}^2$. The plant consisted of 2650 heliostats each with a reflective surface of 115 m^2 to produce 19.9 MWe, and 15 h storage, 6500 h/yr [56,175]. Besides that, to provide reliable electricity according to [175,177,178], the plant was hybridized with natural gas (according to Spanish regulation which allowed by 12–15% hybridization with natural gas). It was operated in April 2011 [176], and it succeeded in generating power at thermal efficiency higher than Solar Two and its storage system succeeded in storing thermal energy per kg of salt three times the stored energy in the storage system of Andasol power plant that has used parabolic trough technology due to its high concentrated heat temperature [169]. Table 8 shows the technical data of the GEMASOLAR plant.

Table 8

Technical data and operation of the Solar Tres (GEMASOLAR) [175,176,179].

Technical data	
Total mirror surface	310,000 m^2
Number of heliostats (SENER mechanism)	2650
Field surface area	185 ha
Nominal receiver capacity	120 MWt
Tower height	140 m
Thermal storage capacity	670 MWhh (15 h)
Turbine capacity	19.9 MWe
Thermal cycle efficiency	40%
Annual normal direct radiation	2.172 kWh/m^2
Operation	
NG hybridization	15%
Annual equivalent hours	6,450 h/yr
Annual capacity factor	74%



Fig. 16. Photo of PS10 in Spain [19].

In 2005, according to [61,188], Abengoa Solar Company built the first water/steam receiver tower plant under pure commercial approach in the world in Sevilla, Sanlúcar la Mayor, Spain. The plant was named Planta Solar 10 (PS10) and it consisted of 624 glass–metal heliostats each of 120 m^2 with total aperture area $75,000 \text{ m}^2$, pressurized-water thermal storage system to avoid the cloud transient storage unit for 50 min at 50% load, saturated-steam receiver (115 m height) and conventional power cycle to generate 11.02 MWe. The plant was operated in 2007 and hybridized with natural gas as stated in [61,188]. To avoid the technical

Table 9
Current projects of tower power technology worldwide.

Break ground year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
2005	June 25, 2007	Planta Solar 10	Abengoa Solar	Sevilla, Sanlúcar la Mayor, Spain	Commercial	2012 kWh/m ² /yr 75,000 m ² water/steam	11.02 MW at 45 bar 250–300 °C	Operational	[188]	Pressurized-water thermal storage system (50 min)
2006	April 22, 2009	Planta Solar 20	Abengoa Solar	Sevilla, Sanlúcar la Mayor, Spain	Commercial	2012 kWh/m ² /yr 150,000 m ² water/steam	20 MW at 45 bar 250–300 °C	Operational	[189]	Pressurized-water thermal storage system (50 min)
July 31, 2007	Dec. 2008	Jülich Solar Tower	Kraftanlagen München; German Aerospace Center, Solar-Institute Jülich	Jülich, Rhineland, Germany	Demonstration	902 kWh/m ² /yr 17,650 m ² air	1.5 MW at – 680 °C	Operational	[186]	Storage system: 1.5 h, ceramic heat sink
July 2008	July 2009	Sierra SunTower	eSolar	Lancaster, California, Los Angeles, U.S.	Commercial	2629 kWh/m ² /yr 27,670 m ² water/steam	5.0 MW at – bar 440 °C	Operational	[190]	It is the only operating solar thermal power plant using tower technology in the United States
–	April 2011	ACME Solar Tower	ACME Group; eSolar	Bikaner, Rajasthan, India	Demonstration	– kWh/m ² /yr 16,222 m ² water/steam	2.5 MW at 60 bar 440 °C	Operational	[184]	
Feb. 2009	April 2011	Gemasolar Therosolar	–	Spain	Commercial	2172 kWh/m ² /yr molten salt	19.9 MW 565 °C	Operational	[56]	Storage system provides 15 h See Table 8
–	May 2011	Lake Cargelligo	Lloyd Energy Systems Pty Ltd	Lake Cargelligo, New South Wales, Australia	Demonstration	kWh/m ² /yr 6080 m ² Water/Steam	3.0 MW at 50 bar 500 °C	Operational	[187]	Storage: core graphite thermal storage technology
July 2009	Aug. 2012	Beijing Badaling	Institute of Electrical Engineering of Chinese Academy of Sciences	Beijing, Yanqing County, China	Demonstration and experimental platform	1290 kWh/m ² /yr 10,000 m ² water/steam	1.5 MW at – 400 °C	Operational	[185]	Fossil backup type: oil-fired boiler storage system: 1 h, two stages, saturated steam/oil
Oct. 1, 2010	Oct. 2013	Ivanpah Solar Electric Generating Station	BrightSource Energy	Primm, NV, California, San Bernardino, United States	Commercial	2717 kWh/m ² /yr 2,600,000 m ²	392.0 MW at 160 bar 1050 F	Under construction	[192]	– Ivanpah 1 has a total capacity of 126 MW and Ivanpah 2 and 3 are both 133 MW each. Fossil back up: natural gas
Nov. 28, 2010	–	Supcon Solar Project	Supcon Solar	Delingha, Qinghai, China	Commercial	– kWh/m ² /yr 434,880 m ² molten salt	50 MW at-bar-	Under construction	[194]	
April 2011	Oct. 2013	Crescent Dunes Solar Energy Project	SolarReserve's	Tonopah, Nevada, Nye, United States	Commercial	2685 kWh/m ² /yr 1,071,361 m ² molten salt	110 MW at 115 bar 1050 F	Under construction	[191]	Direct storage, 10 h
2011	July 2014	BrightSource Coyote Springs 1 (PG&E 3)	BrightSource Energy	Coyote Springs, Nevada, United States	Commercial	–	200 MW	Under development	[195]	
2012	July 2015	BrightSource Coyote Springs 2 (PG&E 4)	BrightSource Energy	Coyote Springs, Nevada, United States	Commercial	–	200 MW	Under development	[196]	
2012	July 2016	BrightSource PG&E 5	BrightSource Energy	TBD, California, United States	Commercial	–	200 MW	Under development	[197]	
Nov. 2012	Nov. 2014	Khi Solar One	Abengoa Solar	Upington, Northern Cape, South Africa	Commercial	– kWh/m ² /yr 576,800 m ² Water/Steam	50 MW at – bar –	Under construction	[193]	Saturated steam storage with 2 h
2013	Dec. 2016	BrightSource PG&E 6	BrightSource Energy	TBD, California, United States	Commercial	–	200 MW	Under development	[198]	
2013	July 2017	BrightSource PG&E 7	BrightSource Energy	TBD, California, United States	Commercial	–	200 MW	Under development	[199]	

problems of the project in order to focus on the scaling up, integrating subsystems, demonstrating dispatchability and reducing the O&M cost the plant's component were tested in PSA facility in Spain before constructing the plant [188]. Then after 1 year, Abengoa Solar Company built the second commercial tower plant named PS20 in the same location after developing significant improvement in the receiver used in PS10 [189]. PS20 consisted of improved receiver (165 m), solar field area included 1255 glass-metal heliostats each 120 m² with total area 150,000 m², pressurized-water thermal storage system (50 min) and conventional power cycle generated 20 MWe. The plant was operated in 2009 [189]. Fig.16 shows photo of PS10 in Spain [19].

5.2. Current projects

Tower power technology is considered a more recent technology than parabolic trough but it is well established since the success of the first commercial PS10 plant [61,204]. Worldwide there are several large scale projects, but these projects as shown in Table 9 are either under construction or planning and most of them in the United States. The technology's peak solar to electricity conversion efficiency, annual solar-to-electricity conversion, water consumption for cooling purposes and land use as stated in [59] reached to 20–27%, 15–17%, 3–4/0.2 m³/MWh and 8–12 m³/MWh/a respectively.

6. Stirling dish technology (SDC)

The power dish technology is a parabolic dish-shaped concentrator, which reflects the DNI of sun's ray to a central receiver located at the focal point of a parabolic dish to produce high temperature heat, above 1000 °C, which then is converted into electricity by generator unit attached to the receiver [17]. The receiver may be a micro-turbine or a Stirling engine, which is the most commonly used. It requires the continuous two-axis tracking system to track the sun's ray throughout the day. The working fluid that is used for driving Stirling engine is either helium or hydrogen. If helium is used as working fluid the Stirling engine type is free piston engine; it does not produce friction during operation that enables a reduction in maintenance cost, while if working fluid is hydrogen the engine type is kinematic engine, which has higher efficiencies than free piston engine [4,206]. The Stirling/dish technology is shown in Fig. 17.

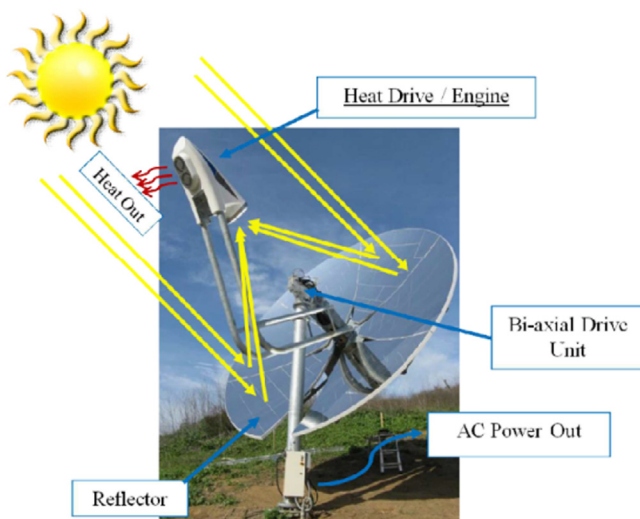


Fig. 17. The Stirling/dish technology [67].

Among all CSP technologies parabolic dish has special design that allows deploying them individually for remote applications, or grouped together for small-grid or end-of-line utility applications, and to place them on uneven terrain or slopes surface [2,16]. Besides that, it has the highest overall efficiency because the generating unit is located attached to the receiver of each dish that leads to reduction in the thermal loss of the technology [206]. The main disadvantages of dish technology are that it cannot integrate with the thermal storage system and the possibility of hybridization with another source of energy is low.

6.1. Historical development

In the late 1970s and early 1980s, as per [206], solar powered steam-Rankine and Stirling-based systems were developed and demonstrated by several companies, which were United Stirling AB, Advanco Corporation, McDonnell Douglas Aerospace Corporation (MDA), NASA's Jet Propulsion Laboratory, and DOE. So among all CSP technologies parabolic dish was considered the oldest technology. Advanco Corporation during the period 1982–1985, as per [206,207], developed Advanco's Vanguard system that consisted of United Stirling 4-95 kinematic Stirling engine, glass-faceted dish; its diameter was 10.5 m and direct insolation receiver in Southern California to generate 25 kWe. The Vanguard system as per [207,208] was tested for 18 months and during these months the system succeeded in converting the solar energy to electrical energy with net conversion efficiency equal to 29.4%, but it reported several technical problems such as failure of check valve of one engine, failure of oil pump shaft of another, repeated failure of circuit boards, vibration and excessive noise. Schlaich-Bergemann und Partner of Stuttgart, Germany in 1984 as in [207], constructed and operated two Stirling dish engines each 17 m-diameter and generated 50 kWe in Riyadh in Al Saudi Arabia Kingdom. The systems used United Stirling 4-275 kinematic Stirling engine and direct insolation receiver, and it achieved a net electrical output of 53 kW with a solar to electric efficiency of 23% at an insolation of 1000 W/m² [206–208].

McDonnell Douglas Aerospace Corporation (MDA) in the mid of 1980s produced 8 prototype dish engines to commercialize the technology, but due to the status of energy market the Corporation canceled all their energy related activities [206,207]. The MDA's prototypes were sold to Southern California Edison (SCE) [206]. The commercial dish engine consisted of the United Stirling 4-95 kinematic Stirling engine, glass-faceted dish; its diameter was 11 m and direct insolation receiver and it was operated from 1986 to 1988 by SCE [207,208]. It converted solar energy to electricity with net efficiencies of about 30%, and in its last year of operation it reported an annual efficiency of about 12% [206].

Cummins Engine Company in the early 1990s, according to [206,207], tried to commercialize dish/Stirling systems by using free-piston engine, instead of kinematic engine in order to reduce the maintenance operation and hence reducing the cost. This effort was supported by Sandia National Laboratories and the National Renewable Energy Laboratory [206]. In 1991, the development program that named dish/Stirling Joint Venture Program (DSJVP) was started to develop a 5–10 kW Stirling system for remote power applications [209], but in 1996 Cummins Engine Company decided to cancel all their activities in development of Cummins' free-piston Stirling engine with big technical problems that could not be resolved [210]. Fortunately in late 1993, another program named Utility Scale Joint Venture Program (USJVP) was started by Science Applications International Corporation (SAIC) and Stirling and Thermal Motors (STM) to develop a 25 kWe dish/Stirling engine system for utility applications [211]. They succeeded in demonstrating a 20 kW Stirling engine (Phase1) in Golden, Colorado [206,208]. Arizona Public Service Company

(APS) in December 1996 partnered with SAIC/STM team to construct and demonstrate the next five prototype dish/Stirling projects during the 1997–1998 [206]. SAIC/STM team used a third-generation version of the STM 4-120, a faceted stretched-membrane dish with a face-down-stow capability, and a directly-illuminated hybrid receiver to produce the new generation named Phase3 in order to reduce the cost with maintaining the demonstrated performance levels. The new generation of the Utility Scale Joint Venture Program according to [206] calls for the deployment of a 1 MWe dish/Stirling engine system.

Stirling Energy Systems (SES) according to [34,214] was installed in May 2005 which was a prototype of Stirling/dish power plant at Sandia's National Solar Thermal Test Facility (NSTTF) named Serial #3 to produce 150 kWe by using 6-unit arrays (SunCatcher), each using 82 mirrors and hydrogen as HTF to generate 25 kWe. As stated in the same articles on 31 Jan 2008 with the sky almost 10% brighter than usual Serial#3 generates electricity with net solar-to-grid conversion efficiency of 31.25%. Fig. 18 shows photo of Serial#3 at Sandia National Laboratories [34]. Since 2005, according to [214], Sandia's CSP team and SES have worked together to improve the design and the operation of the Stirling/dish system. Their efforts resulted in producing new refined design named SunCatcher™, which is the next-generation model of the original SunCatcher system and it was tested through installing prototype consisting of four dishes at (NSTTF). Fig. 19 shows photo of four SunCatcher™ dishes at Sandia National Laboratories. The new design has improved optics, and it is lighter than the original system design by about 5000 pound because it uses 40 precision mirrors instead of 82 mirrors, has round shape



Fig. 18. Photo of Serial#3 at Sandia National Laboratories [34].



Fig. 19. Photo of four SunCatcher™ dishes at Sandia National Laboratories [214].



Fig. 20. Photo of Maricopa Solar project in Arizona, United States [213].

instead of the rectangular shape that allowed more efficient use of steel and consists of 60% fewer engine parts [214].

In September 2009, Stirling Energy Systems (SES) built the first demonstrated plant in Arizona, United States, which was composed of 60-SunCatcher™ dish units each 25 kWe to generate 1.5 MWe with zero water consumption for cooling purposes [212,213]. The plant started production in January 2010 with annual solar-to-electricity gross efficiency equal to 26% and it was decommissioned in September 2011 because Stirling Energy Systems (SES) was filed for bankruptcy [213]. Fig. 20 shows the Maricopa Solar project in Arizona, United States.

Currently, many technological improvements are developed by the developer's technology in order to reduce the cost of the technology by finding new support structure design aimed to reduce the number of parts and the amount of steel, optimizing the mirror facets to enable faster installation on site as well as the adoption of high volume manufacturing mirrors, development of the storage system to develop storage solution for the technology and improving the engine design to improve the output capacity and the efficiency of the technology.

6.2. Current projects

Table 10 shows that the technology has only one commercial project, and it is still under construction. This implies that the technology is still commercially unavailable although its peak solar to electricity conversion efficiency ranges from 29.4% to 31.25%, annual solar-to-electricity conversion efficiency of 26% and operating temperature reached to 250–700 °C, which are higher than all CSP technologies. It does not consume water for cooling purposes, and it uses land similar to tower technology. However, the land use for any technology is important only if the technology will be used in the area next to existing power plant or in urban area where land availability is limited.

7. Summary of the solar thermal technologies

Solar thermal technologies include four technologies named as parabolic trough collector (PTC), tower solar power (TSP), Stirling/dish collector (SDC) and linear Fresnel collector (LFC) with its advance type named compact linear Fresnel collector (CLFC).

7.1. PTC technology

PTC is a mature technology. It is proven technically and commercially. Also the possibility of hybridizing it with conventional plants and/or integrating it with the storage system is proven. Furthermore, when it is integrated with the storage system the LCOE becomes low, compared with LFC and TSP technologies (see Table 11). Currently around the world there are

Table 10

Current projects of Stirling/dish technology worldwide.

Break ground Year	Start production year	Project name	Company	Location/country	Project type	Solar resource, field area and HTF	Capacity	Status	Source	Note
Aug. 17, 2012	2013	Tooele Army Depot	Infinia Corp.	Tooele County, Utah, Tooele, U.S.	Commercial	~kWh/m ² /yr 35 m ² helium	1.5 MW	Under construction	[212]	

Table 11

Summary of the solar thermal technologies.

CSP technologies	Parabolic trough	Linear Fresnel collector	Tower power	Stirling dish
Principle of operation	Concentrates solar radiation on linear tube receiver mounted on the parabolic collector	Concentrates solar radiation on elevated inverted linear fixed receivers on the flat collector	Concentrates solar radiation on a point receiver at the top of a tower	Concentrates solar radiation on a point receiver attached to Stirling engine
Technique	Uses line focus [17,25]	Uses line focus [17,24]	Uses point focus [17,18]	Uses point focus [17]
Tracking system	1-axis [17,25]	1-axis [17,24]	2-axis [17,18]	2-axis [17]
Application	Uses for grid-connected plants and industrial heat process applications	Uses for grid-connected plants, solar cooling and industrial heat process applications	Uses for grid-connected large scale plants	Uses individually for remote applications, or grouped together for small-grid or end-of-line utility applications
First demonstration for the technology	Ericsson's reflector used to generate steam to drive his Stirling engine in 1864 [52]	LFC prototype at Lacédémone-Marseilles solar station by Francia in 1959 [30]	EURELIOS generated 1 MWe in 1978 [6156]	Advanco's Vanguard system by Advanco Corporation generated 25 kW during 1982–1985 [206,207]
First demonstration plant	Was built in 1913 in Maadi, Egypt for irrigation purpose [60]	Was built by Israeli Paz Company in 1991 [31]	For water as HTF: Solar One generated 10 MWe in 1981 [171,205] For molten salt as HTF: Solar Two generated 10 MWe in 1996 [183]	a 25 kWe dish/Stirling engine system for utility applications developed under USJVP by SAIC and STM in the late 1993 [211]
First commercial plant	SEGS I has generated 14 MWe since 1984 [71,74,216,217]	CLFR plant beside Stanwell power station has generated 14 MWe since 2000 [30]	For water as HTF: PS10 has generated 10 MWe since 2007 [61,188] For molten salt as HTF: Gemasolar has generated 19.9 MW since 2011 [56]	Tooele Army Depot plant still under construction will generate 1.5 MWe [212]
Peak solar to electricity conversion efficiency	23–27% [59]	18–22% [59]	20–27% [59]	29.4–31.25% [207][208] [34] and [214]
Annual solar-to-electricity conversion	15–16% [59]	8–10% [59]	15–17% [59]	26% [213]
Water consumption, for wet/dry cooling (m ³ /MWh)	3–4/0.2 [59]	3–4/0.2 [59]	3–4/0.2 [59]	0 [212,213]
Land use (m ² /MWh/a)	6–8 [59]	4–6 [59]	8–12 [59]	8–12 [212,213]
Cost/kWh for generating 100 MWe at 2000 kWh/m ² yr	0.265 euro/kWh without storage/0.187 euro/kWh with storage [215]	0.230 euro/kWh with buffer [215]	0.230 euro/kWh with storage [215]	–
Cost/kWh for generating 100 MWe at 2500 kWh/m ² yr	0.210 euro/kWh without storage/0.163 euro/kWh with storage [215]	0.200 euro/kWh with buffer [215]	0.200 euro/kWh with storage [215]	–
Storage unit type & (h)	Direct & indirect storage (molten salt) 0.5–12 [see Table 4]	Buffer (water) 0.5–1 [see Table 6]	Buffer (water)/direct storage (molten salt) 1–15 [see Table 9]	0
Operating temperature (°C)	310–393 (therminol oil), 340 (water), 550 (molten salt) [see Table 4]	250–300 (water-HTF) [see Table 6]	250–500 (water), 565 (molten salt), 680 (air) [see Table 9]	250–700 (hydrogen or helium) [34,214]
Current projects	No. of project 62	No. of project 6	No. of project 8	No. of project 0
Total capacity of Operating plants	2751.41 MWe	59.65 MWe	64.42 MWe	0 MWe
Country of operating plants	Spain (40), Italy (1), U.S. (14), U.A.E.(1), Iran (2), Thailand (1), Algeria (1), Egypt (1), Morocco (1)	Spain (2), France (1), Australia (2), U.S. (1)	Spain (3), Germany (1), U.S. (1), India (1), China (1), Australia (1)	–
Total capacity of Under construction plants	20 2122 MWe	5 166 MWe	4 602 MWe	1 1.5 MWe
Country of under construction plants	Spain (6), U.S. (3), Mexico (1), India (6), Morocco (2), South Africa (1), Chile (1)	India (1), Australia (1), France (2), Morocco (1)	U.S. (1), China (1), South Africa (1)	U.S. (1)
Total capacity of Under development plants	4 400 MWe	0 0 MWe	5 1000 MWe	0 0 MWe
Country of under development plants	U.S. (3), South Africa (1)	–	U.S. (5)	–

62 operational PTC projects with total generating capacity 2751.41 MWe (95.7% of the total generating capacity of the operational CSP projects); 20 under-construction projects with total generating capacity 2122 MWe (73.4% of the total generating

capacity of the under-construction CSP projects) and 4 under-development projects with total generating capacity 400 MWe (28.57% of the total generating capacity of the under-development CSP projects) (refer Fig. 21). As seen the number of operational

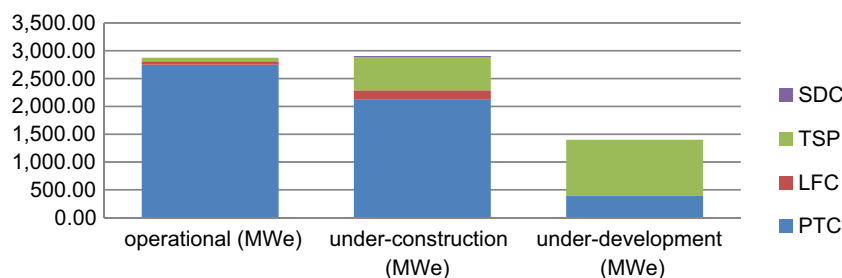


Fig. 21. The generating capacity of CSP operational, under-construction and under-development projects, BY technology.

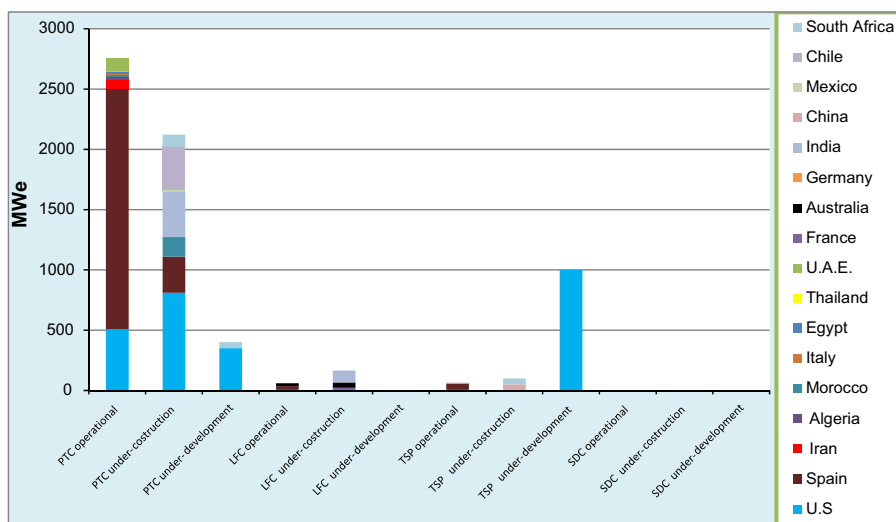


Fig. 22. The generating capacity of CSP operational, under-construction and under-development projects, BY country and technology.

projects is approximately three times the number of under-construction projects, but the total capacity of operational projects and under-construction projects are approximately same. This means that, the most of the under-construction projects are large scale projects, and this trend aims to decrease the LCOE and hence make the technology competitive with conventional plants. The operational projects are distributed as follows: 14 projects (509.16 MWe) in the U.S., 40 projects (2 GWe) in Spain and 8 projects (242.25 MWe) in the these countries: Iran (2 projects generate 67.25 MWe), Algeria (1 project generates 25 MWe), Morocco (1 project generates 20 MWe), Italy (1 project generates 5 MWe), Egypt (1project generates 20 MWe), Thailand (1projects generates 5 MWe) and the U.A.E. (1project generates 100 MWe) (refer Fig. 22). The under-construction projects are distributed as follows: 3 projects in U.S. (810 MWe), 6 projects in Spain (300 MWe) and 11 projects in the following countries: Mexico (1 project with capacity 14 MWe), India (6 projects with total capacity 375 MWe), Morocco (2 projects with total capacity 163 MWe), Chile (1 project with capacity 360 MWe) and South Africa (1 project with capacity 100 MW) (refer Fig. 22). The under-development projects are distributed as follows: 3 projects (350 MWe) in the U.S. and 1 project (50 MWe) in South Africa (refer Fig. 22). Although the U.S. is the first country constructing and operating nine PTC plants (354 MWe), Spain is considered the pioneer country in the use of the PTC technology with 40 operational projects generating 2 GWe, compared with 14 operational projects in the U.S. generating 509.16 MWe (refer Fig. 22). In the MENA region that includes Net Oil-Exporting Countries (NOEC) and Net Oil-Importing Countries (NIEC) there are only few countries that have used the technology for generating clean electricity. Among the (NOEC) countries only Iran, Algeria, Egypt and U.A.E. have used this technology; and currently U.A.E. is

considered the pioneer country in the use of the technology by 1 project which generates 100 MWe. Among the Net Oil-Importing Countries (NIEC) Morocco is the only country that has used this technology, and it will be the pioneer country in the MENA after operating 2 under-construction projects with total capacity of 163 MWe (refer Fig. 22). Since PTC technology is a mature technology, all the operational, under-construction and under-development projects are commercial projects, and they include 33 pure solar plant; 11 hybrid solar-fossil fuel plants; 8 ISCC plants; 32 hybrid solar-storage units plants; 1 hybrid solar-fossil fuel-storage unit plant; and 1 hybrid solar-existing fossil fuel plant. All of them use oil as HTF except two projects each that produce 5 MWe; one in Italy uses molten salt as HTF and the other in Thailand uses water as HTF. Currently, to increase the overall efficiency of PTC solar plant the developers of the technology have studied the opportunities to improve the output temperature and the overall efficiency of the solar field by finding alternatives for the heat transfer fluid instead of using oil as HTF.

7.2. LFC technology

The LFC technology is still in the experimental stage. It has the lowest efficiencies among all the CSP technologies, and when its optical efficiency is improved it will become the direct competitor for PTC technology. Moreover, among all the CSP technologies this technology has the lowest land use, and this advantage makes it the best choice when the land area is limited such as in urban areas or when we want to hybrid the technology with existing conventional plant; and the free land area next to the plant is limited. Currently there are only 6 operational projects with generating capacity 59.65 MWe (2.07% of the total generating capacity of operational CSP projects) and 5 under-construction

projects with generating capacity 166 MWe (5.74% of the total generating capacity of under-construction CSP projects) (refer Fig. 21) around the world and the most of them are prototypes. As seen the number of under-construction is less than the number of operational projects, but the total capacity of under-construction projects is approximately 2.8 times the total capacity of operational projects. This means that, the most of the under-construction projects are large scale projects, and this trend also aims to decrease the LCOE and hence make the technology competitive with conventional plants. The operational projects are 1 project in the U.S. (5 MWe), 2 projects in Spain (31.4 MWe), 1 project in France (0.25 MWe) and 2 projects in Australia (23 MWe) (refer Fig. 22). The under-construction projects are 1 project in Australia (44 MWe), 1 project in India (100 MWe), 1 project in Morocco (1 MWe) and 2 projects in France (21 MWe) (refer Fig. 22). It is worth noting that, among the mentioned countries, currently Spain is also the pioneer country in the use of the LFC technology, but India has under-construction project with installed capacity 100 MWe; this project will make India in the near future the pioneer country in the use of this technology. Among the MENA countries Morocco is the only country that has used the LFC technology. The LFC technology projects worldwide include 2 prototype projects, which are 1 pure solar plant and 1 solar-single tank storage plant, 3 pure solar demonstration projects and 6 commercial projects, which are 3 hybrid solar-existing coal plants, 2 pure solar plants and 1 solar-single tank storage plant. All these projects use water as HTF.

7.3. TSP or central receiver technology

Tower power technology is considered a more recent technology than PTC technology, but it is well established since the success of the first commercial PS10 plant that was built in 2007. The possibility of integrating it with the storage system is proven. From the economic side it is preferred to use TSP technology for large scale utility power plants because it needs large scale receiver and high number of expensive heliostats and hence large amount of space more than other PTC and LFC technologies. Currently there are 8 operational projects with generating capacity 64.42 MWe (2.24% of the total generating capacity of the operational CSP projects), 4 under-construction projects with generating capacity 602 MWe (20.8% of the total generating capacity of under-construction CSP projects) and 5 under-development projects with generating capacity 1000 MWe (71.43% of the total generating capacity of the under-development CSP projects) (refer Fig. 21). The operational projects are as follows: 1 project (5 MW) in the U.S., 3 projects (50.92 MWe) in Spain, 1 project (1.5 MWe) in Germany, 1 project (2.5 MWe) in India, 1 project (3 MWe) in Australia and 1 project (1.5 MWe) in China (refer Fig. 22). The under-construction projects are 2 projects (502 MWe) in the U.S., 1 project (50 MWe) in China and 1 project (50 MWe) in South Africa (refer Fig. 22). The under-development projects are all in the U.S (refer Fig. 22). It is worth mentioning that, currently Spain is also the pioneer in STP technology with 3 operational projects generating 50.92 MWe, but the U.S. excels in future projects whereby, it has 2 under-construction projects with total capacity of 502 MWe and 5 under-development projects with total capacity of 1000 MWe. It is also worth noting that, there is growth in the use of STP technology, and all the projects either under-construction projects or under-development projects are large scale projects; this is in order to commercialize the technology through decreasing the capital cost of the technology and hence decreasing the LCOE. Besides that, this trend aims to make the technology competitive with conventional plants and PTC plants as shown in Table 11; at the same value of DNI the LCOE for 100 MWe PTC plant with the storage system is lower than the

LCOE for 100 MWe STP plant with the storage system. The STP projects worldwide include 13 commercial projects (2 pure solar plants, 5 hybrid solar-storage units plants, 1 hybrid solar-fossil fuel plant and 5 projects are undefined) and 4 demonstration projects (2 solar-single tank storage project, 1 pure solar project and 1 hybrid solar-coal – storage system project). 8 of these projects use water HTF, 3 use molten salt HTF and 1 use air HTF.

7.4. SDC technology

SDC technology has a special design so that it can be used individually for remote applications, or grouped together for small-grid or end-of-line utility applications, and to place them on uneven terrain or slopes surface. Among all the CSP technologies this technology has the highest overall efficiency and highest operating temperature that reached to 250–700 °C. Moreover, it has zero water consumption, for the wet/dry cooling system. Although, currently the technology has only one under-construction commercial project in the U.S. (refer Fig. 22). This is because the cost of the technology is still prohibitive and it cannot integrate it with the thermal storage system and the possibility of hybridization with another source of energy is low. The generating capacity of this project is 1.5 MWe (0.052% of the total generating capacity of under-construction CSP projects) (refer Fig. 21).

These technologies are summarized in Table 11.

8. Discussion and conclusion

Among all CSP technologies PTC is the dominant technology in the present time in which as shown in Fig. 21 the share of the PTC technology in the total generating capacity of CSP projects (operational, under-construction and under-development projects) reached to 73.58%, compared with 3.15% from the LFC technology, 23.25% from TSP technology and 0.021% from SDC technology. The share of PTC, LFC, TSP and SDC technologies in the total generating capacity of operational CSP projects are 95.77%, 2.07%, 2.24% and 0% respectively, in under-construction CSP projects are 73.4%, 5.74%, 20.82% and 0.052% respectively, and in under-development projects are 28.57%; 0%; 71.43% and 0% respectively (refer Fig. 21). As shown from this figure, PTC is a dominant technology in the operational and under-construction projects because it is considered the optimum choice to utilize the solar radiation to generate clean electricity with lower potential risk by the investors, but its share in under-construction projects reduced to 73.4%, compared to 95.77% in operational projects; at the same time the share of the LFC technology, TSP technology and SDC technology in under-construction projects reached to 5.74%, 20.82% and 0.052% respectively, compared with 2.07%, 2.24% and 0% respectively in the operational projects this is because there is a trend toward the use of the other technologies especially the LFC and TSP technologies as a result of improvement in the performance of these technologies. For under-development CSP projects the TSP technology is the dominant technology in which the use of TSP technology for generating clean electricity reached 71.43%, compared with 28.57% for PTC technology. Consequently we can predict that, among all the CSP technologies PTC and TSP technologies will be the dominant technologies in the future because these technologies can be integrated with direct or indirect storage system that can store the heat for more than 10 h, and this advantage makes these technologies compete with the fossil fuel technologies.

Worldwide, the total operational CSP projects are 76 with total capacity of 2.88 GWe distributed as follows: 16 projects with capacity 519.16 MWe in the U.S., 45 projects with capacity 2.1 GWe in Spain, 2 projects with capacity 67.25 MWe in Iran, 1 project with capacity 25 MWe in Algeria, 1 project with capacity

20 MWe in Morocco, 1 project with capacity 5 MWe in Italy, 1 project with capacity 20 MWe in Egypt, 1 project with capacity 5 MWe in Thailand, 1 project with capacity 100 MWe in U.A.E., 1 project with capacity 0.25 MWe in France, 3 projects with capacity 26 MWe in Australia, 1 project with capacity 1.5 MWe in Germany, 1 project with capacity 2.5 MWe in India and 1 project with capacity 1.5 MWe in China (refer Fig. 23). The total under-construction CSP projects are 30 with total capacity of 2.892 GWe, which is approximately equal to the total generating capacity of the operational CSP projects distributed as follows: 6 projects with capacity 1313.5 MWe in the U.S., 6 projects with capacity 300 MWe in Spain, 1 project with capacity 14 MWe in Mexico, 7 projects with total capacity 475 MWe in India, 3 projects with total capacity 164 MWe in Morocco, 1 project with capacity

369 MWe in Chile, 2 projects with capacity 150 MWe in South Africa, 1 project with capacity 44 MWe in Australia and 2 projects with capacity 21 MWe in France (refer Fig. 23). The total under-development CSP projects are 9 with total capacity of 1400 MWe that is approximately half the total generating capacity of the operational CSP projects distributed as follows: 8 projects with capacity 1350 MWe in the U.S. and 1 project with capacity 50 MWe in South Africa (refer Fig. 23).

As shown in Fig. 23 currently Spain is the pioneer country in the use of the CSP technologies despite the fact that U.S. is the first country in the world that has implemented, developed and marketed the CSP technologies; but in the near future, the U.S. will regain its position through the implementation of the 14 projects with a total capacity of 2663.5 MWe distributed as follows: 3 under-

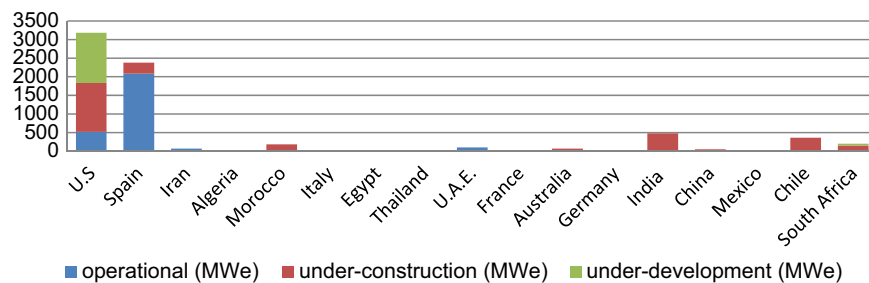


Fig. 23. The generating capacity of CSP operational, under-construction and under-development projects, BY country.

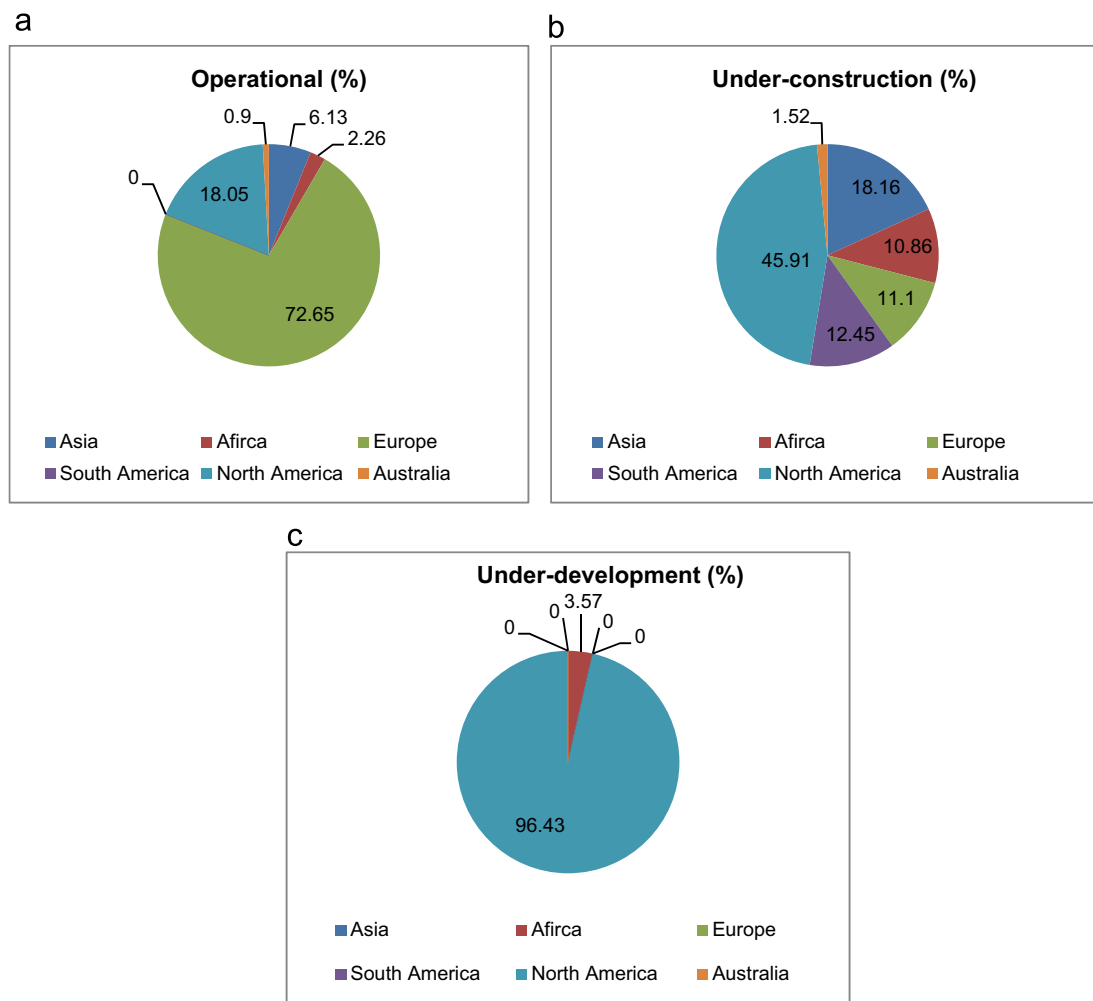


Fig. 24. The generating capacity of CSP operational, under-construction and under-development projects, BY continent.

construction PTC projects (810 MWe), 2 under-construction TSP projects (502 MWe), 1 under-construction SDC project (1.5 MWe), 3 under-development PTC projects (350 MWe) and 5 under-development TSP projects (1000 MWe). In Asia, currently U.A.E. is the pioneer country in the use of the CSP technologies with 1 project generating 100 MWe, but India has under-construction projects that will generate 475 MWe. In Africa, Algeria; Morocco and Egypt are the pioneer countries for the use of the CSP technologies and each has 1 project which generates 25 MWe, 20 MWe, and 20 MWe respectively, but Morocco and South Africa are more interesting in the use of CSP technologies. They have under-construction projects that will generate 164 MWe and 150 MWe correspondingly.

As shown in Fig. 24(a–c) most of the operational CSP projects are in Europe (72.65% of the total generating capacity of the operational CSP projects) followed by North America (18.05%), Asia (6.13%), Africa (2.26%), Australia (0.9%) and South America (0%), while for the under-construction projects most of them are in North America (45.91% of the total generating capacity of the under-construction CSP projects) followed by Asia (18.16%), South America (12.45%), Europe (11.1%), Africa (10.86%) and Australia (1.52%); and for the under-development projects most of them are in South America (96.43% of the total generating capacity of the under-development CSP projects) and the rest are in Africa (3.57%). This figure shows that, due to the gain in the CSP technologies good reputation the interest in the use of the CSP technologies for generating clean electricity in the world is growing especially in North America, Asia and Africa continents that are considered the promising markets for these technologies because they have all the necessary conditions to implement these technologies successfully. However, the growth in the use of the CSP technologies to generate clean electricity is expected to keep growing at a significant pace whereby, according to the study conducted by Greenpeace, the European Solar Thermal Power Industry (ESTIA) and the International Energy Agency (IEA) [240] projected that, the global CSP capacity could reach 37 GW by 2025 and 600 GW by 2040. But, according to the study conducted by IEA–ETSAP and IRENA [241] projected that, the global CSP capacity would reach to 150 GW by 2020 and 350 GW by 2030 because the CSP technologies will become economically competitive with fossil fuel technologies due to increase in the prices of the fuels and CO₂ and reduction in the cost of solar technologies.

As a general conclusion the historical development of solar thermal technologies showed that PTC technology is the most technically and commercially successful technology. This technology is considered mature, and it is able to provide the required operating heat energy either as a stand-alone or in hybrid systems at the lowest cost and lower economic risks. It is operated in commercial projects for more than 28 years. LFC technology used with water as HTF is the main competitor for the PTC technology in producing low cost electricity if its cosine effect is reduced. However CLFC technology helps in reducing the cosine effect and hence improves the optical efficiency. Tower Power technology is also a competitor to PTC in producing low cost electricity if the cost of heliostats and receiver decreased. However, it is preferred to be use for large-scale solar plant. Stirling/dish technology is the oldest technology and has the highest solar-to-electricity conversion efficiency and zero water consumption, but it is commercially unavailable because its cost is prohibitive.

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